

multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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2. ABSTRACT

The rapid advancement of digital technologies, combined with the growing complexity of infrastructure systems and their exposure to multi-hazard risks, is profoundly transforming the skills required of personnel involved in the management of critical infrastructures. In this context, Task T6.5 – Re-skilling and Up-skilling of the Asset Management Workforce focuses on exploring the most promising innovative technologies to promote digital, multidisciplinary, and sustainable training for the asset management workforce involved in the operation of Critical Infrastructures. This deliverable describes the methodologies and digital tools adopted to enhance workforce training, leveraging advanced Educational Technologies (EdTech) and updated pedagogical approaches. It reports on the implementation and evaluation of three technological prototypes: (i) a natural language chatbot for OpenBIM data interaction, (ii) an immersive Virtual Reality serious game for operational and inspection training, and (iii) a holographic-based learning environment, demonstrating how digital tools can support experiential, context-aware, and scalable learning pathways. The document also describes cross-competence development activities grounded in Design Thinking, which foster creativity, problem-framing capabilities, and user-centred solution design.

Furthermore, the deliverable introduces the architecture of an integrated Knowledge Hub Platform, a modular environment that consolidates training resources, technical documentation, collaborative spaces, and AI-driven support systems to enable continuous upskilling and knowledge sharing. Collectively, these components contribute to the development of the Resilient Operator, a professional capable of interacting effectively with digital infrastructures, adapting to evolving operational scenarios, and supporting organisational resilience.

Overall, the deliverable outlines methodological, technological, and organisational insights for designing next-generation training solutions aimed at strengthening the preparedness and competence of the critical infrastructure workforce.

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4. Introduction

Critical infrastructures (CIs) constitute the essential operational layer of contemporary societies. Their continuity is fundamental to economic stability, population safety and the functioning of interconnected socio-technical systems. Increasing interdependencies among infrastructure networks, combined with exposure to natural, technological and hybrid hazards, have significantly amplified systemic vulnerability. Emerging stressors such as climate-change-induced extremes, cyberattacks, supply chain instability and geopolitical disruptions highlight the need to strengthen both technical robustness and human-centred operational resilience.

Within this scenario, Asset Management (AM) has evolved into a strategic function integrating performance optimisation, lifecycle planning, safety management and sustainability objectives. The digitalisation of infrastructures, driven by Artificial Intelligence (AI), the Internet of Things (IoT), pervasive sensing, automation, Big Data analytics and Digital Twins (DTs), has fundamentally reshaped operational workflows. Advanced monitoring, predictive maintenance and real-time diagnostics improve situational awareness but simultaneously introduce new layers of complexity that require updated professional competencies.

This technological transition is generating a widening skills gap across infrastructure-intensive organisations. Operators, engineers and maintenance personnel are increasingly required to interpret heterogeneous data streams, interact with digital models, coordinate across multi-disciplinary processes and operate effectively under uncertainty. Capabilities such as data literacy, systems thinking, adaptive decision-making and cross-domain communication are becoming as critical as traditional engineering expertise.

Consequently, workforce development must evolve beyond conventional training paradigms based on classroom teaching and procedural instruction. Contemporary operational environments require active, simulation-based and experiential learning models capable of replicating the temporal, spatial and cognitive demands of real infrastructure operations. Over the last two decades, pedagogical approaches such as problem-based learning, design thinking, scenario-based training and reflective practice have been recognised as effective for enhancing analytical skills, collaborative behaviours and resilience-oriented reasoning.

In this context, Educational Technologies (EdTech) provide enabling mechanisms for the modernisation of training processes. EdTech encompasses a spectrum of digital solutions—Learning Management Systems (LMS), mobile learning applications, AI-driven tutoring systems, serious games, holographic interfaces, and immersive environments such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). When applied to infrastructure management, these technologies support the creation of controlled, repeatable and risk-free environments for practising inspection routines, emergency response procedures, asset-maintenance workflows and multi-actor coordination tasks. Furthermore, data-driven platforms allow the integration of performance analytics, adaptive feedback and personalised learning paths.

The increasing availability of BIM-based models, sensor-generated datasets, and real-time operational information strengthens the potential of simulation-based and XR-enabled training ecosystems. Digital Twins and XR platforms enable multi-scenario simulations with high levels of fidelity, supporting the development of situational awareness, error recognition, procedural accuracy and decision-making under stress. Training therefore becomes an iterative process where users operate within virtualised replicas of real assets, receive immediate feedback and progressively consolidate their competencies.

Parallel developments in industrial and construction paradigms such as Industry 5.0 and Construction 5.0 underscore the need for human-centric, resilient and technologically augmented operators. This evolution frames the concept of the Resilient Operator: a professional capable of interacting with intelligent systems, adapting to dynamic operational conditions and ensuring service continuity across complex infrastructure environments.

5. Stakeholder mapping

Understanding who constitutes the asset management workforce is a fundamental step in designing effective training strategies for the governance and operation of Critical Infrastructures (CIs). To this end, a stakeholder mapping exercise was conducted—developed in synergy with the activities of TS3—to identify the actors involved across the entire infrastructure value chain. The resulting representation highlights the breadth and heterogeneity of the ecosystem, which encompasses a wide range of public and private entities operating at different spatial, organisational and operational levels.

Critical Infrastructure Operators and Technical Workforce. This group includes asset managers, operations personnel, engineers, maintenance teams, safety managers, and training managers. They constitute the operational core of infrastructure systems, ensuring day-to-day functionality, service continuity, and the execution of monitoring, diagnostics, intervention, and maintenance activities throughout the asset lifecycle.

Training needs and digital skills:

- Advanced understanding of digital twins, BIM/OpenBIM models, and IoT-enabled monitoring systems
- Data literacy for interpreting sensor data, dashboards, and predictive analytics
- Competence with automated and AI-assisted diagnostic tools
- Use of digital platforms for asset lifecycle management, maintenance planning, and incident reporting
- Simulation-based training for operational procedures and risk scenarios

Governance, Regulatory and Oversight Bodies. This category comprises regulatory authorities, public administrations, inspection agencies, and institutions responsible for setting standards, overseeing safety, and ensuring regulatory compliance. They play a strategic role in multi-level coordination, risk management, and long-term infrastructural planning.

Training needs and digital skills:

- Understanding of digital governance frameworks, cyber-physical risk, and data-driven regulation
- Skills in using decision-support tools, GIS platforms, and multi-risk assessment systems
- Ability to interpret large-scale infrastructure datasets and compliance dashboards
- Familiarity with simulation tools for scenario planning and policy testing
- Knowledge of digital auditing, traceability systems, and automated reporting workflows

Emergency-Management and Public-Safety Organisations. This group includes Civil Protection agencies, Fire Department, State Police, Medical Rescue, Carabinieri Force, and other response organisations. They operate across preparedness, response, and recovery phases, intervening in high-complexity scenarios that require interagency coordination, rapid decision-making, and the ability to act under pressure.

Training needs and digital skills:

- Use of real-time information systems, command-and-control platforms, and geospatial tools
- XR-based simulation training (VR/AR/MR) for emergency scenarios, evacuation, and hazardous environments
- Competence in drone operations, remote sensing, and digital field-reporting tools
- Data literacy for validating and acting upon real-time alerts, sensor streams, and predictive hazard models
- Ability to operate interoperable communication systems across agencies and infrastructure operators
- Cyber awareness, especially during events involving cascading cyber-physical impacts

Education, Training and Certification Ecosystem. This cluster encompasses universities, vocational training centres, instructors, professional trainers, and certification bodies. It supports continuous workforce development and prepares future generations entering the infrastructure sector, thereby influencing the quality, evolution, and long-term sustainability of professional competencies.

Training needs and digital skills:

- Capacity to design digitally enabled, multidisciplinary training pathways aligned with emerging technologies
- Familiarity with EdTech tools such as LMS platforms, serious games, and VR/AR training modules
- Competence in developing digital assessments, microcredentials, and skills certification systems
- Ability to integrate real infrastructure datasets, digital twins, and simulation environments into curricula
- Knowledge of instructional design methodologies suitable for complex socio-technical systems

The stakeholder map represented in the figure clearly illustrates the systemic dimension of the challenge: the resilience of critical infrastructures depends on the coordinated action of a wide plurality of actors, each bringing specific responsibilities, knowledge domains and operational constraints. The interaction between these groups highlights the need for transversal competences, shared situational awareness and interoperable training solutions capable of bridging organisational boundaries.

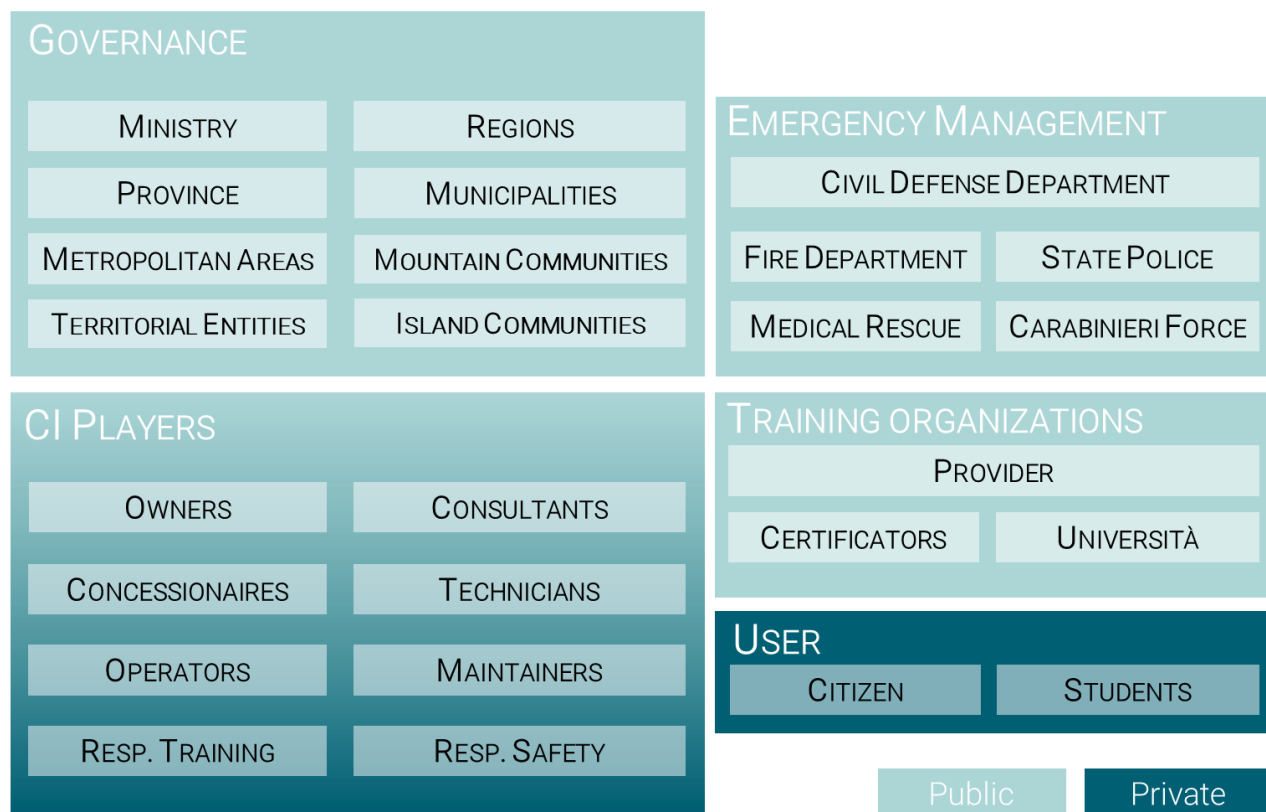


Figure 1: Asset management workforce stakeholder map

The topic of training is inherently complex and positioned at the intersection of multiple macro-systems: the built environment and critical infrastructure, the natural environment in which these assets are embedded, and the emergency-management domain. This overarching system must continuously respond to immediate shocks—such as natural hazard events—as well as to long-term pressures including climate change, urbanisation, economic crises, and other systemic stressors.

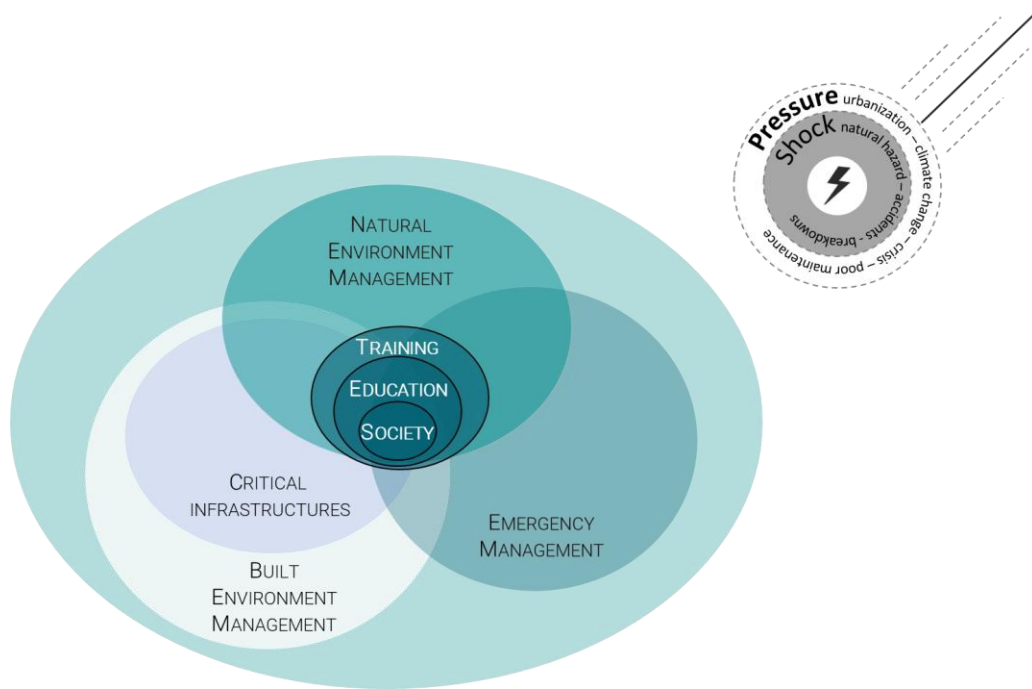


Figure 2: System map of the training problem space

6. Education Technology

The digital transformation of critical infrastructures is reshaping the skills required of their management and operational personnel. Within this framework, Education Technology (EdTech) plays a central role in fostering re-skilling and up-skilling processes, enabling adaptive, data-driven, and experiential forms of learning.

EdTech integrates a variety of tools - ranging from immersive environments and simulation systems to AI-driven adaptive platforms - that enhance both technical competence and situational awareness in complex operational contexts.

To ground the RETURN project's training activities in a solid scientific foundation, this section draws upon the outcomes of the systematic review entitled "*Rethinking Education on Critical Infrastructure Resilience and Risk Management: Insights from a Systematic Review*" (see [Annex 1](#)). This review provides a comprehensive synthesis of current approaches, identifying emerging technologies and methodological trends that can improve the performance, capability, and awareness of personnel involved in the management of critical infrastructures. The systematic review analyses more than a decade of international research exploring how digital, cognitive, and immersive technologies can support professional development in high-risk and data-intensive environments. The findings highlight several key methodological and technological domains relevant to the RETURN framework.

7. Practical Implementations and Experimentation

7.1 Chatbot

7.1.1 Objectives

The increasing complexity of digital models and data environments in critical infrastructure management calls for new interfaces that facilitate intuitive and meaningful access to information. The collaboration between human intelligence and Artificial Intelligence (AI), enabled by Large Language Models (LLMs), introduces new perspectives for interpreting this complexity. LLMs enhance the narrative, semantic richness, and accessibility of digital models, transforming them into intelligible representations that can be explored even by non-expert users in the field.

This pilot explores the use of a chatbot as a cognitive interpretation tool capable of improving understanding and knowledge extraction from Building Information Modelling (BIM) data systems. Within the context of a CI, the chatbot acts both as a training assistant and as an intelligent knowledge interface enabling users to query and navigate complex OpenBIM datasets through natural language. The overall objective is to foster data accessibility, knowledge retention, and training efficiency for personnel engaged in asset management and maintenance, thus bridging the gap between digital complexity and human operational practice.

7.1.2 Methodological approach

The operational workflow is designed to enable bidirectional communication between the user and the BIM information models enriched with data relevant to the management and maintenance of critical infrastructures. The chatbot acts as a semantic interpreter, translating natural language requests into executable commands within the digital model environment.

Operational Flow

1. The user formulates a query in natural language (e.g., “Select all pipes” or “Show me elements with parameter level equal to 0”).
2. The chatbot interprets and classifies the request using Natural Language Processing (NLP) techniques, identifying the user’s intent and relevant entities.
3. The chatbot sends the corresponding command to the BIM environment through API-based communication, triggering the appropriate Python function within Blender.
4. The BIM software executes the requested operation, for instance, filtering or selecting specific objects, and displays the results in the viewer for immediate visual feedback.

This workflow establishes a natural-language interface to access both graphical and alphanumeric information, effectively transforming the BIM model into an interactive digital knowledge base.

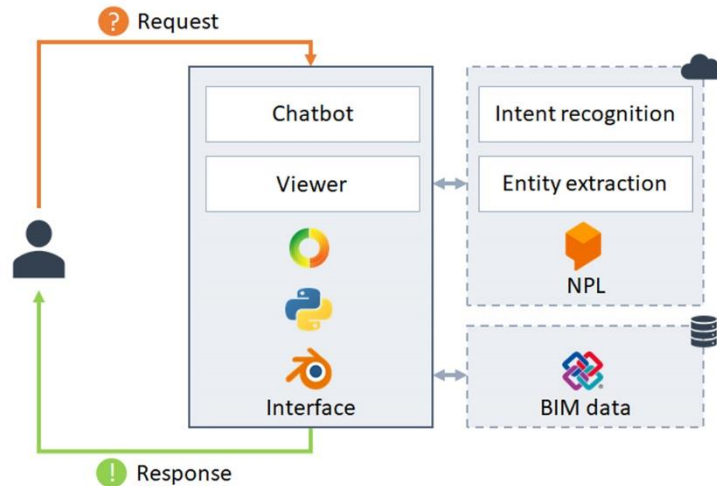


Figure 3: Architecture of the technical solution

System Architecture

The System Architecture consists of two main components.

- **Chatbot Interface:** Responsible for managing the communication between the user and the BIM software. It employs NLP technologies for Intent Recognition and Entity Extraction, using dedicated APIs to interact with the BIM database and perform data-driven operations. for Intent Recognition and Entity Extraction.
- **3D Viewer:** Enables the real-time visualisation of the BIM model within the same interface. This component supports intuitive exploration of both visual and informational data, reinforcing the cognitive link between model geometry and metadata.

Software Tools and Data Workflow

The digital model was authored in Autodesk Revit 2024, selected because it is one of the most widely used BIM authoring tools in the architecture, engineering, and construction (AEC) industry and therefore ensures high interoperability and compatibility with other platforms and workflows. The model was then exported in IFC4 format to guarantee full OpenBIM data exchange and long-term accessibility across different software ecosystems.

For model interaction, Blender 4.2 was adopted with the Bonsai add-on (developed by IfcOpenShell), as it offers extensive capabilities for rendering, animation, simulation, and the manipulation of complex 3D geometries within a single workspace.

Communication between Blender and the chatbot is handled by a custom plugin developed in Python, which integrates a chatbot created in Dialogflow. This plugin enables seamless API communication between the NLP module and the 3D environment, allowing the execution of contextual functions such as element selection, filtering, or counting.

The first step is to design the NLP module in Dialogflow through the creation of *Intents* and *Entities*, following best practices described in Amershi et al. (2019) to ensure a smooth and natural conversational experience.

- Entities were defined to enrich intent understanding and identify target data in user queries.

They are realised according to the context of the domain in which they are used and must be associated with a specific intent. As a non-exhaustive example, the Entity Class used in the Intent 'Class_Selection' to select objects based on their IFC class is shown. The aim is to make the virtual assistant recognise IFC classes by synonyms. For example, we want the class IfcPipeSegment to be recognised by entering the word 'pipe' to facilitate conversation. Consequently, the agent reacts to the sentence 'select all the door' by correctly identifying the Intent and recognising the parameter 'class' equal to 'IfcDoor'.

Class

Entity	Synonyms
IfcWindow	Finestra, Windows, Window, IfcWindows, Finestre
IfcDoor	Porta, Door, IfcDoor, Porte
IfcWall	IfcWall, Muri, Muro, Wall, Walls
IfcSlab	IfcSlab, floor, pavement, covering
IfcPipeSegment	IfcPipeSegment, pipe
IfcPipeFitting	IfcPipeSegment, pipe
IfcValve	
IfcRoof	

Agent

USER SAYS: select all the doot

DEFAULT RESPONSE: I have select the IfcDoor

INTENT: Class_Selection

ACTION: Not available

PARAMETER	VALUE
seleziona	select
class	IfcDoor

SENTIMENT: Query Score: 0.0

DIAGNOSTIC INFO

Figure 4: Example of setting up Entities on Dialogflow

- Intents were configured to trigger specific functions once a user's request was correctly classified.

Their definition included: (i) the configuration of training phrases for NLP classification; (ii) the insertion of multiple Entities to create the parameters required for API calls; (iii) and a testing phase to validate the chatbot's responses. For instance, the intent `Select_byParameterValue` was set to identify both the parameter name and its value in a request such as "Show me the elements with parameter level equal to 0", recognising "level" as the parameter and "0" as the value.

Select_byPamameterValue

Training phrases

Template phrases are deprecated and will be ignored in training time. More details here.

When a user says something similar to a training phrase, Dialogflow matches it to the intent. You don't have to create an exhaustive list. Dialogflow will fill out the list with similar expressions. To extract parameter values, use annotations with available system or custom entity types.

95 Add user expression

95 please, highlight the objects with parameter class equal to Wall

95 can you select all the object with parameter date equal to today?

95 all elements with parameter Installation equal to 06/05/2024

95 all elements with parameter type equal to type1

95 Select elements with parameter WBS equal to 00_00

95 Select elements with parameter WBS equal to 00_00

Action and parameters

Enter action name

REQUIRED	PARAMETER NAME	ENTITY	VALUE	IS LIST
☐	name	@Parameter	\$name	☐
☐	value	@Value	\$value	☐
☐	Enter name	Enter entity	Enter value	☐

Agent

USER SAYS: show me the element with parameter level equal to 0

INTENT: Select_byPamameterValue

ACTION: Not available

PARAMETER	VALUE
value	0
name	level

SENTIMENT: Query Score: -

Figure 5: Example of Intent setting on Dialogflow

The integration of the NLP module with the Blender interface takes place through the use of the Scripting section of the program, allowing the execution of Python scripts that communicate via API with the Dialogflow server. Once the BIM data were imported in IFC format, specific functions could be executed thanks to Intent and Entity recognition, leveraging the IfcOpenShell libraries to access and manipulate model information directly. This configuration establishes a closed-loop interaction where natural-language input, data interpretation, and 3D visual feedback coexist in real time, enabling operators and trainees to engage with complex infrastructure data in an accessible, immersive, and learning-oriented environment.

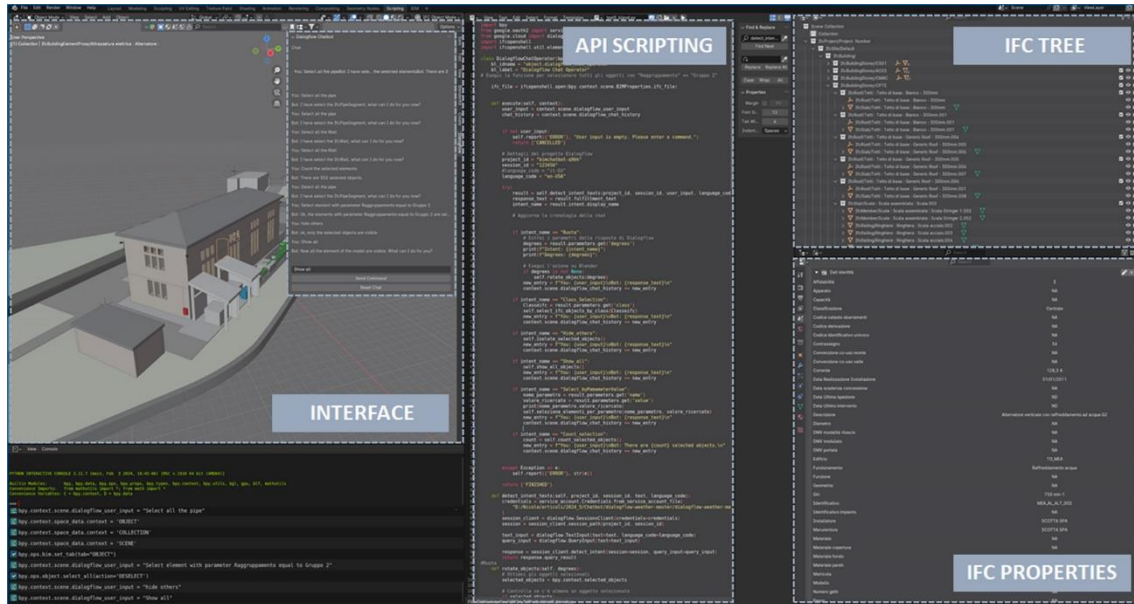


Figure 6: Blender Scripting interface for prototype development

7.1.3 Use case implementation

The architecture of the technical solution described above was implemented through an actual case study to validate the approach. The realised prototype aims to query the graphic and alphanumeric database resulting from a standardised digitalisation process of a large hydroelectric power plant park. The chatbot fulfils the need to access the complex structure of the BIM database and intuitively, even by non-expert personnel, to consult the master data of the main components making up the plants for management and maintenance purposes.



Figure 7: Meano hydroelectric power station in Pomaretto (TO) used as a case study



Figure 8: Workflow implementation of the case study

Autodesk Revit 2024 was used as BIM authoring software. Subsequently, it was exported in IFC4 format and imported into Blender 4.2 via the Add-on Bonsai9, developed by IfcOpenShell and available free online. The Python programming language makes it possible to link Dialogflow with specific Blender functions via API, such as selecting or counting elements via natural language. Once the workflow has been established, it is possible to talk to the chatbot to send requests to the Dialogflow agent.

A series of explanatory use cases are proposed for:

- The identification of items, either by class – e.g., all pipes or concerning the value of a specific parameter – electrical and mechanical equipment, which are about the same electrical production group.

At the start of the conversation, the chatbot tells the user what he can do; simultaneously, the Blender interface shows the IFC model (Fig. 9, point 1). Next, the user is asked to select ‘pipe’ elements. By recognising the Intent ‘Class_Selection’, a script can select elements with the required IFC class (Fig. 9, point 2), as previously described. To facilitate the identification of the elements of interest, the user asks to hide the other objects (Fig. 9, point 3), and the chatbot executes the script associated with the specific Intent. The conversation continues with the user requesting to select the objects by value, requesting the Intent ‘Select_byParameterValue’ by specifying the parameter name ‘Grouping’ (Fig. 11, point 4) and the value ‘Group 2’ (Fig. 9, point 5).

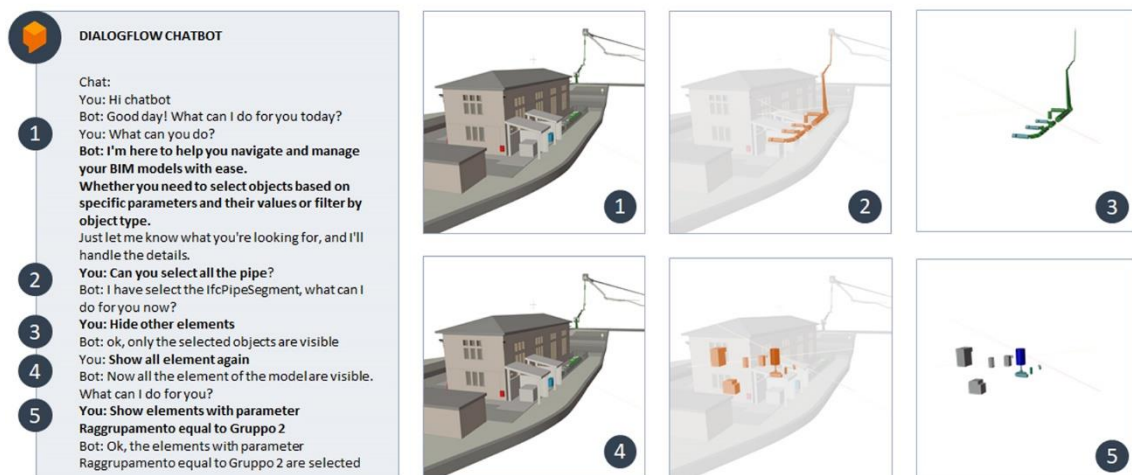


Figure 9: Example of conversation with natural language element selection

- b) The counting of items with specific characteristics, such as the equipment maintained by a particular person on a specific date.

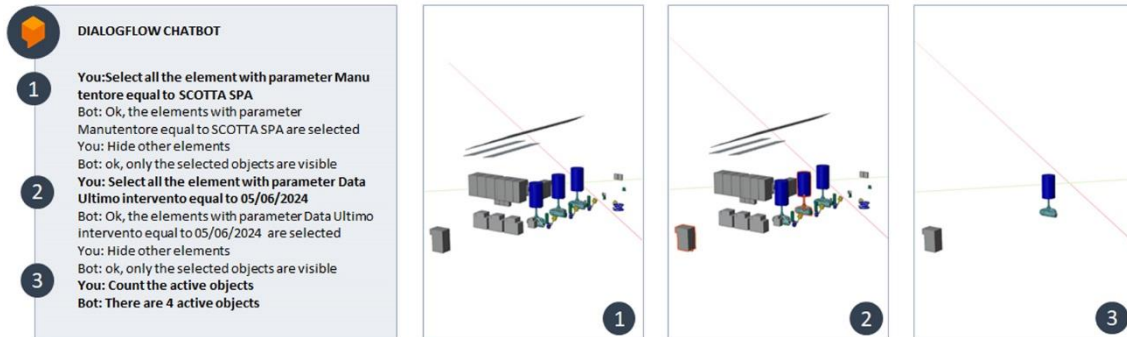


Figure 10: Example of conversation with natural language element counting

7.1.4 Impact

The chatbot prototype demonstrated the feasibility of integrating NLP and AI interfaces with OpenBIM environments for both training and operational purposes in the context of critical infrastructures.

This experimentation confirms that AI-assisted interaction can provide a valuable educational and operational tool for asset management personnel, bridging the gap between complex digital models and human understanding. Main results and benefits:

- Improved data accessibility: even non-specialist users can easily retrieve technical information without navigating complex modelling software or database interfaces.
- Enhanced learning and cognitive retention: the conversational approach supports experiential and contextual learning, promoting active knowledge acquisition.
- Scalability and interoperability: the framework can be adapted to other infrastructure typologies—such as water networks, energy grids, and transport systems—thanks to its OpenBIM-based architecture.
- Increased workforce capability: by simplifying the access to technical and maintenance data, the system contributes to up-skilling and re-skilling of operators, aligning training processes with the goals of the RETURN project.

7.2 Serious game

7.2.1 Objectives

The increasing structural and operational complexity of critical infrastructures requires training solutions capable of supporting accurate system comprehension, risk awareness, and procedural reliability. Literature in the fields of human-machine interaction, immersive simulation, and safety engineering highlights the effectiveness of Virtual Reality Serious Games (VR-SGs) in reproducing hazardous or restricted environments and in enabling controlled, repeatable training conditions.

The objective of this prototype is to evaluate the feasibility and effectiveness of an immersive VR Serious Game as a technical training tool for complex infrastructural systems. The prototype is designed to consolidate heterogeneous technical content, such as operational procedures, safety protocols, and process documentation, into a unified, interactive simulation environment that replicates real operational scenarios.

The overarching goal is to foster intuitive comprehension of infrastructure processes, strengthen users' ability to recognise risks and operational conditions, and improve training effectiveness for diverse user profiles, ranging from non-expert visitors to professional operators. Immersive environments are used to support safe exploration and contextualised guidance, aligning training content and difficulty with the needs of critical-infrastructure management.

7.2.2 Methodological approach

The methodological approach is grounded in the integration of immersive simulation, digital modelling, and interaction-driven training strategies. The prototype adopts a multi-layer framework combining:

- **Virtual Reality** technologies to reproduce spatial conditions, operational sequences, and restricted-access zones in a safe and controlled manner.
- **Building Information Modelling** for the geometric and semantic representation of infrastructural assets, ensuring consistency between virtual and real operational environments.
- Interactive procedural modelling, enabling the encoding of standard operating procedures, risk categories, and maintenance workflows into dynamic, executable training scenarios.
- **AI**-supported interaction modules, based on Large Language Models (LLMs), to facilitate context-aware guidance, adaptive feedback, and advanced information retrieval during training sessions.

The methodology focuses on translating heterogeneous technical content into structured digital workflows. Scenario design follows a task-oriented approach, mapping each operational activity onto a sequence of verifiable user interactions. This approach allows for monitoring user performance, validating procedural compliance, and ensuring fidelity between training dynamics and real operational practices.

This combination allows the creation of realistic scenarios enriched with procedures, safety information, operational actions and simulations. The approach replaces traditional static learning methods—such as manuals and supervised visits—with dynamic experiences that enhance comprehension, engagement, and decision-making capabilities.

System Architecture

The architecture is based on a multilayer pipeline that integrates heterogeneous data sources, digital models, interaction systems, and intelligent services. Its goal is to transform technical and documentary information into a navigable virtual environment that is consistent with the real infrastructure and equipped with advanced user-support functionalities.

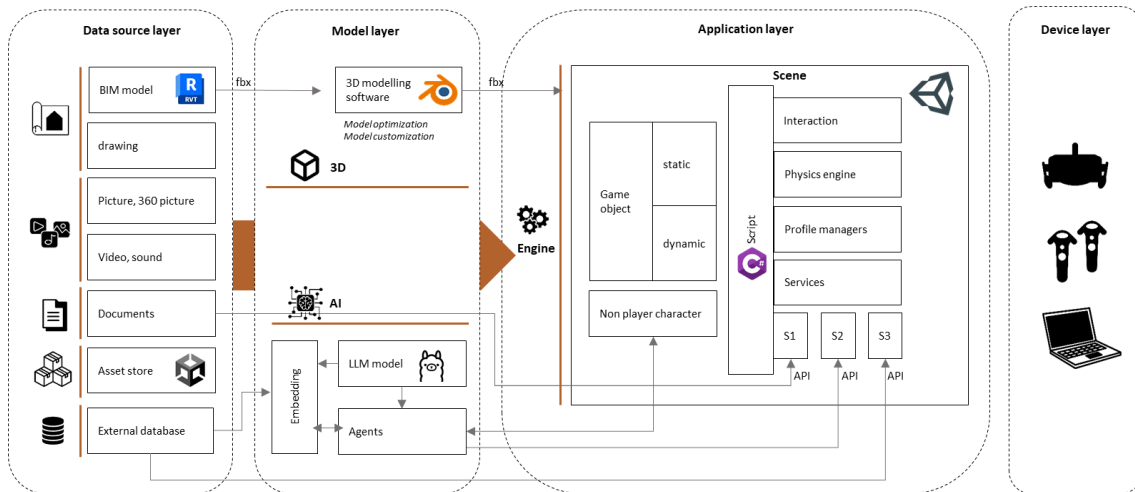


Figure 11: System architecture

The **Data Source Layer** gathers all the inputs required to feed the system. The BIM model of the critical infrastructure, developed in Autodesk Revit 2024, provides the geometric and informational foundation of the virtual environment and serves as the primary source for generating the 3D assets used in the simulation. Alongside the BIM-derived data, multimedia materials such as audio descriptions, operational videos, and 360° panoramic images contribute realistic and contextual references. Technical documentation—manuals, procedures, safety guidelines, and risk registers—as well as structured information from operational databases, supplies the content required for knowledge retrieval and AI-based guidance. External asset-store resources further enrich the scene by providing additional graphical elements and objects not included in the original BIM model.

The **Model Layer** handles the transformation of raw input data into assets and structures that can be directly used within the game engine. The BIM model exported from Autodesk Revit 2024 is imported into a 3D modelling software such as Blender, where it undergoes mesh cleaning, reduction, topology adjustments, texture remapping, and material refinement to ensure performance and visual coherence in real-time rendering. Additional scene elements, such as signage, indicators, props, and character models, are created or enhanced in this layer to support the narrative and functional requirements of the immersive experience. This workflow ensures that a BIM model originally conceived for design and documentation becomes a performant and visually coherent asset suitable for VR environments. In parallel, the Model Layer manages the preparation of the content required for knowledge-retrieval functionalities and orchestrates the AI-driven processes that interface with these contents. Technical documents, safety manuals, procedures, as well as structured information coming from internal or external databases, are segmented into smaller units and converted into vector embeddings, which are then stored in a semantic database such as ChromaDB. A retrieval pipeline based on LangChain orchestrates semantic search over this database and forwards the most relevant passages to the language model when queried by the user. A local language model, executed through Ollama, is also instantiated in this layer, forming the computational basis for AI-assisted guidance and contextual interpretation and enabling the system to dynamically access and interpret both documents and database records.

The **Application Layer** is responsible for orchestrating the runtime behaviour of the immersive serious game and integrates all components that enable scene composition, user interaction, and intelligent services. In this layer, the assets produced in the Model Layer are instantiated as game objects within the game engine, where they acquire the visual, physical, and behavioural properties required for execution. The scene is constructed by placing BIM-derived models, props, non-player characters, and multimedia elements into a coherent spatial layout. The environment is configured with materials, colliders, animations, lighting, spatial audio, and environmental effects to ensure consistency and navigability. Once the scene is assembled, C# scripts define the behaviour of the system. These scripts handle user interactions, such as activating points of interest, navigating the environment, or triggering procedural steps, as well as physics, collisions, role-based logic, and validation of operational actions. Through this scripting layer, the environment becomes reactive, operationally meaningful, and capable of supporting task-based learning. The Application Layer also integrates external and intelligent services through dedicated API calls. C# scripts communicate with local or remote endpoints to retrieve data, trigger functionalities, or update contextual information. AI-driven queries are routed to the semantic search and LLM components described in the Model Layer, allowing the system to provide context-aware explanations and adaptive guidance directly within the VR environment.

The **Device Layer** defines the hardware configuration through which the immersive serious game is executed and experienced. It includes all the physical components responsible for running the application, rendering the environment, and enabling user interaction within the virtual space. At the core of this layer is the computer workstation, which provides the computational resources required to execute the game engine, render the 3D environment, and manage the AI-driven services accessed through API calls. The performance of the workstation, particularly its GPU, CPU, and RAM, directly influences the fluidity of the immersive experience, the fidelity of real-time rendering, and the responsiveness of user interactions. User engagement with the virtual environment is enabled through VR head-mounted displays (HMDs), which provide stereoscopic rendering, head-tracking capabilities, and an immersive field of view that reproduces the scale and spatial characteristics of the infrastructure being simulated. The HMD ensures spatial presence and allows users to perceive depth, distance, and environmental cues consistent with real-world operations. Interaction within the VR environment is further supported by handheld controllers, which allow users to navigate, select objects, activate interactive elements, and perform actions associated with training procedures. The controllers' tracking systems translate hand gestures and movements into in-world interactions, enabling precise manipulation of objects, activation of scripts, and execution of task sequences. Combined, these devices establish the physical interface between the user and the application, ensuring that the immersive training environment is not only visually coherent but also operationally usable, responsive, and aligned with the functional demands of critical-infrastructure training.

7.2.3 Use case implementation

The Safety & Operations Training Hub (SOTH) serves as the demonstrative use case for evaluating the potential of immersive technologies in the context of critical-infrastructure training. The prototype has been developed around the simulation of a wastewater treatment plant, where articulated processes, restricted operational areas, and multiple risk categories are only partially conveyed through manuals, technical documentation, and supervised site visits. SOTH addresses these limitations through an experiential design approach that integrates narrative, interactivity, and advanced digital technologies. By immersing users in a virtual representation of the plant enriched with information, procedures, actions, and simulated scenarios, the system enables safe exploration of complex processes and supports the development of decision-making skills without exposing operators to real hazards. The prototype has been conceived as an immersive, role-based training environment capable of supporting both educational exploration and operational training. It leverages BIM-derived models for geometric accuracy, VR technologies for spatial immersion, and AI-driven interactions based on Large Language Models to provide contextual guidance. This integration makes it possible to transform procedural manuals, safety documents, and risk registers into adaptive, context-aware instructions tailored to the user's role and position within the plant.



Figure 12: Safety & Operations Training Hub

The training experience is structured around three user profiles, each with specific objectives and interaction modes:

- **Visitor profile**

This profile targets non-expert users approaching the plant for educational or outreach purposes. The system offers a guided narrative pathway that introduces the main components of the wastewater treatment process—from the screening unit to final disinfection—and provides access to both the water line and the sludge line. Interactive elements such as dynamic illustrations, highlighted components, animations, and audio-guided explanations help users understand process flows and regulatory requirements concerning effluent quality. The focus for this profile is on accessibility, intuitive comprehension, and general awareness.

- **Operator profile**

Technical operators require a deeper understanding of operational procedures, equipment behaviour, and safety practices. For this profile, SOTH simulates control, monitoring, and maintenance tasks through interactive checklists and task-based scenarios. Users can inspect parameters, identify anomalies, and access video-guided procedures illustrating correct interventions. The simulation also presents the main operational hazards, biological risks from aerosols and microorganisms, explosion risks from biogas in anaerobic digesters, and chemical risks related to corrosive substances, supported by animations, hazard indicators, and informational panels. The objective is to strengthen procedural adherence, situational awareness, and safe decision-making.

- **Inspector profile**

The inspector profile is designed for users responsible for assessment, verification, and compliance monitoring. This mode allows users to navigate the plant with access to inspection-specific tools, such as system overviews, risk maps, documentation linking, and contextual queries supported by the integrated AI mechanisms. Inspectors can review operational conditions, verify that procedures are followed correctly, examine safety-related information, and assess plant conformity with regulatory requirements. This profile focuses on analytical capabilities, risk identification, and the evaluation of safety measures within the virtual environment.

Within this use case, the Safety & Operations Training Hub operates explicitly as a serious game in which the wastewater treatment plant becomes a playable environment for infrastructure training. The three profiles described above are interpreted as distinct ways of engaging with the same virtual plant, each associated with different objectives, tools, and evaluation criteria. Visitors focus on process understanding and general awareness, operators on execution and monitoring of procedures, and inspectors on verification and documentation of safety conditions. The learner overview figure “Learner specifics” visualises this structure by presenting the three profiles as separate entry points that share a common spatial and information backbone while accessing different layers of interaction and feedback.

This role-based framing ensures continuity with the methodological approach. The same BIM-derived geometry, interactive procedures, and AI-assisted information services are reused across profiles, but filtered according to the responsibilities and permissions associated with each role. In practice, this means that the serious game does not create three different worlds, but a single virtual infrastructure that supports multiple training perspectives.



Figure 13: Learner specifics

The temporal organisation of the serious game, summarised in the “Storyline” figure, defines each session as a mission with a clear beginning, middle, and end. A single-entry scene establishes the configuration of the run; from there, the story branches into three normal-operation paths that correspond to the water line, the sludge line, or a combined full path; these paths can be temporarily diverted into sudden-hazard episodes; and all trajectories converge in a common debriefing scene. In this way, the figure encodes the overall rhythm of the game configuration, exposure to the process under normal conditions, optional disruption through hazards, and structured closure without yet detailing what happens in each scene, which is addressed in the subsequent figures.

The same storyline is shared by all three user profiles and by the main hazard families, which are mapped alongside the flow. This makes the figure a compact representation of how the methodological choices are operationalised in practice: task-oriented interactions are grouped into coherent missions along the water or sludge line; hazard simulations are attached to those missions rather than treated as isolated events; and the final debriefing provides a stable place where performance across runs, roles, and risk types can be compared. The “Storyline” diagram therefore functions less as a list of scenes and more as a structural template that organises how scenarios are composed, repeated, and evaluated within the overall training platform.

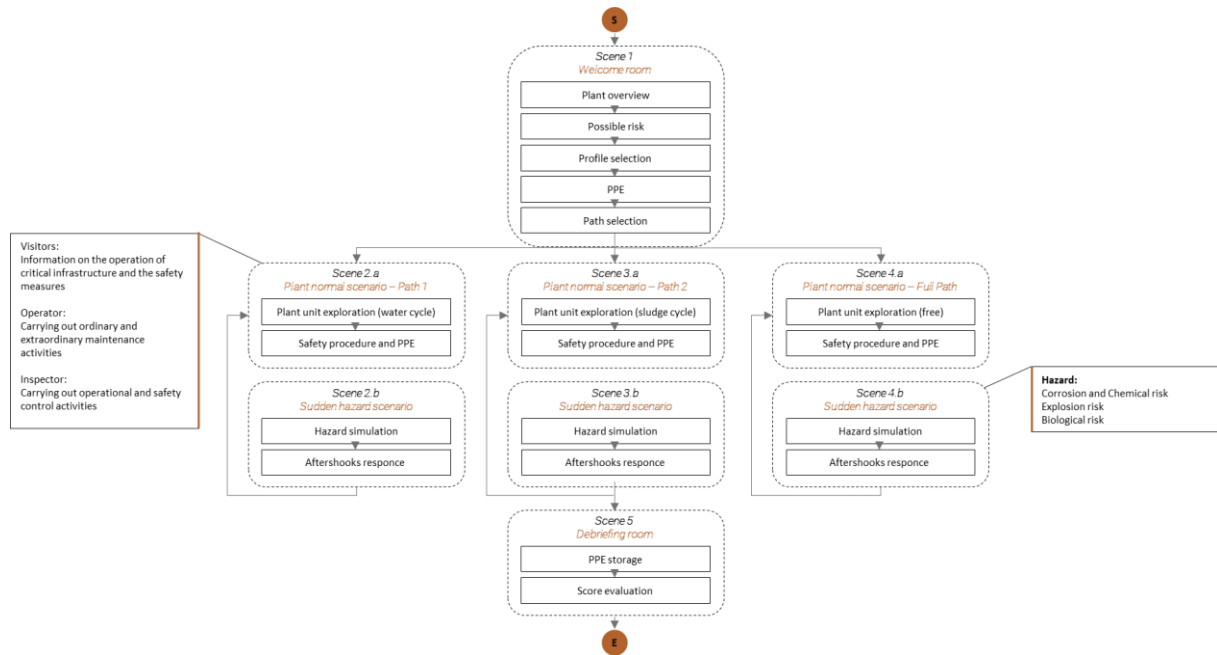


Figure 14: Storyline

The Welcome room is the first scene in which the serious game becomes concrete for the user. As shown in the dedicated figure, the space is structured into five functional areas: plant overview, infrastructure-related risks, profile selection, personal protective equipment (PPE), and path selection. In the plant overview area, a simplified representation of the wastewater treatment process introduces the main units and highlights the relation between water and sludge paths. The risk area recalls the main hazard categories relevant for the plant, aligning the immersive scenario with the risk taxonomy used in documentation and risk registers.

In the profile selection area, users confirm the visitor, operator, or inspector mode, linking the abstract learner types to an actual game configuration. The PPE area recalls mandatory equipment for the chosen role and, where relevant, for the selected path, reinforcing the connection between digital training and real safety requirements. Finally, the path selection area at number 5, allows users to choose between the water, sludge, or full plant trajectories defined in the storyline.

Welcome room

- 1 Plant overview
- 2 Infrastructure-related risks
- 3 Profile selection
- 4 Personal Protective Equipment
- 5 Path selection



Figure 15: Welcome room

Path

Challenges

- Maintenance activity
- Equipment movement
- Fluid dynamics
- LLM integration

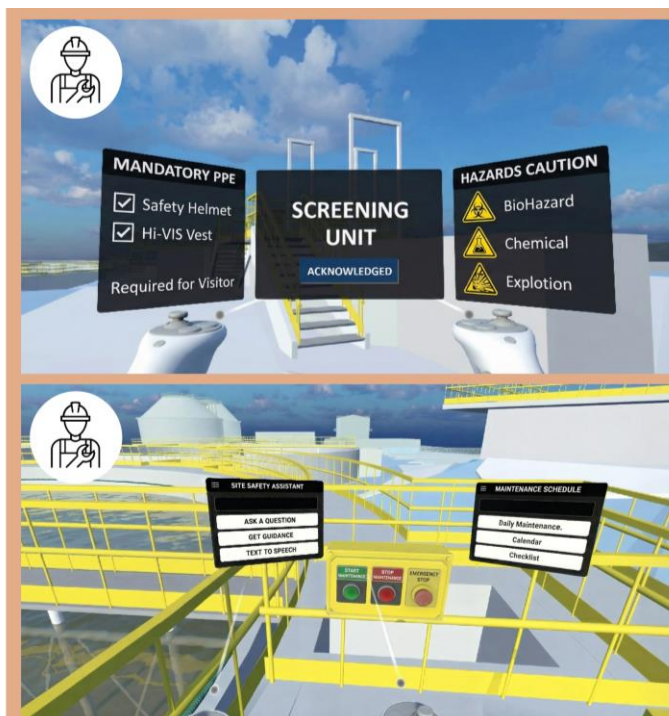


Figure 16: Operator interactions within the screening unit of the water treatment line

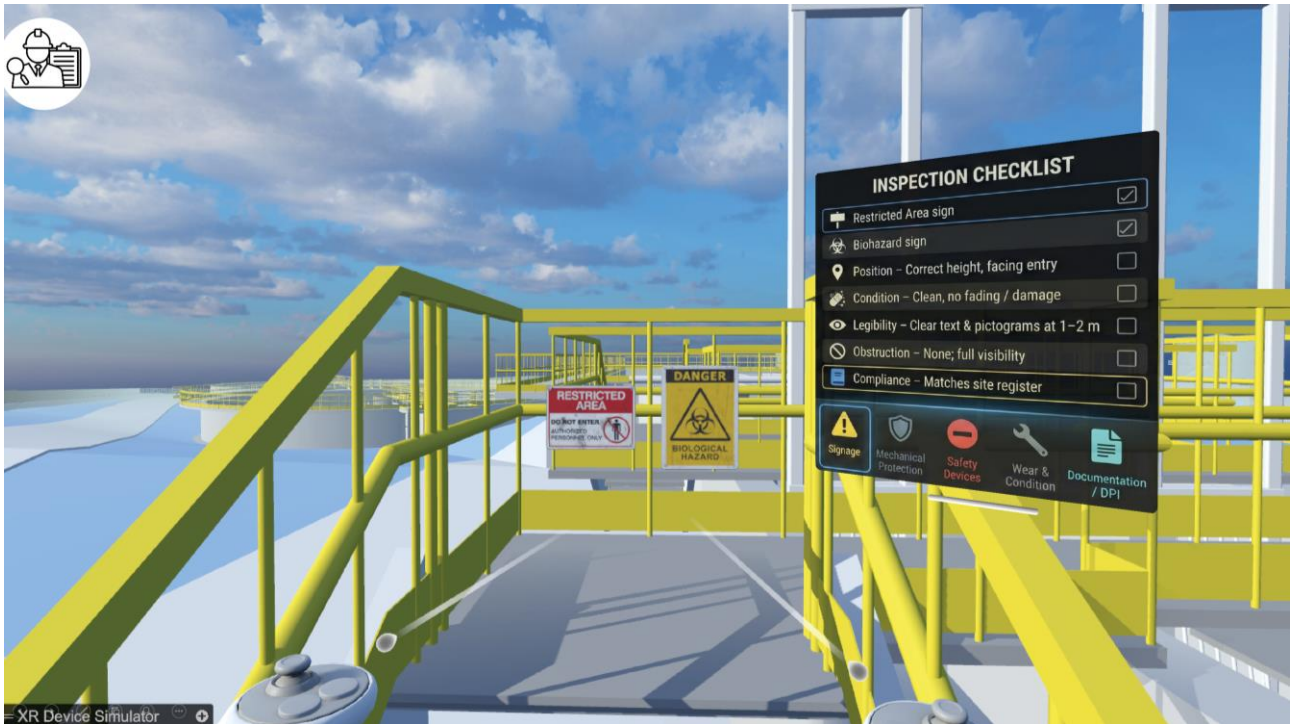


Figure 17: Inspector interactions within the screening unit of the water treatment line

Once the configuration is completed, the user is placed on the corresponding path within the virtual plant. In the operator path, represented in the figure 16, the user appears on walkways and platforms near equipment and local control points. World-anchored panels provide information about mandatory PPE, local hazards, and maintenance requirements, while interactive checklists and task lists support operational activities such as inspections, cleaning, and functional tests. Through these panels, operators can trigger procedural steps, record completion of actions, and, where necessary, query the AI-supported assistant for short, context-aware clarifications based on the technical documentation encoded in the Model Layer.

In the inspector path, shown in figure 17, the same physical locations are augmented with verification tools instead of operational controls. Inspection panels are organised into thematic tabs, such as signage, mechanical protection, safety devices, wear and condition, and documentation/DPI. Each item corresponds to a concrete requirement, for example the presence and correct positioning of safety signs, the integrity of guards, or the accessibility of emergency stops. Inspectors move along the platforms and corridors, observe the scene, and record findings directly in the virtual environment. In this way, inspection practice is turned into a repeatable, measurable interaction sequence aligned with real procedures and regulatory expectations.

Debriefing and KPI measurement

At the end of the path, all profiles converge in a debriefing scene that closes the serious game loop and reconnects the immersive session with the wider customised training platform. In this space, the system aggregates the main elements of the session: selected role and path, visited units, encountered hazard scenarios, completed tasks, and inspection outcomes. For visitors, the emphasis is on which process stages and key messages have been covered; for operators, on the execution of operational steps and responses to abnormal conditions; and for inspectors, on the completeness of inspection coverage and identification of non-conformities.

To make these results evaluable, the system logs relevant user actions as discrete events (for example visited units, activated panels, completed checklist items, and responses to hazard scenarios). These events are

aggregated into profile-specific KPIs such as path coverage and content access for visitors, task and procedure completion for operators, and inspection coverage and non-conformity detection for inspectors. Indicators are presented in the debriefing scene for individual feedback and can be exported or referenced alongside knowledge repositories, classroom activities, and site visits, enabling longitudinal monitoring of training performance and aligning the serious game with the broader training ecosystem. Because the storyline and indicators remain stable across runs, these measures can be compared over multiple sessions for the same user or across different user groups.

7.2.4 Impact

The implementation of the Serious Game shows how immersive technologies can be applied in training for critical infrastructures.

- **Improved safety awareness**, through repeated exposure to realistic but risk-free representations of hazards, signage, and restricted zones.
- **Stronger procedural reliability and decision-making**, as users rehearse task sequences and responses to abnormal conditions with immediate feedback and AI-supported guidance.
- **Increased accessibility to complex operational areas**, allowing staff, students, and visitors to experience units that are normally difficult or impossible to access during normal operation.
- **Evidence-based evaluation of training**, enabled by logging interactions and computing profile-specific KPIs on path coverage, task completion, and inspection performance.
- **Higher engagement and learning effectiveness**, especially for non-expert audiences, thanks to interactive scenes that embed explanations directly in the plant context.
- **Reusability and transfer to other infrastructures**, since the BIM-to-VR pipeline and AI-assisted information layer can be applied to additional facilities within the customised training platform.

Overall, SOTH illustrates how experiential design and immersive technologies can update technical training practices in the water sector, supporting safer, more informed, and more resilient operations.

7.3 Holographic technology

7.3.1 Objectives

Holographic technology represents a paradigm shift in education, offering immersive, interactive, and culturally rich learning experiences.

The objective of this research is to examine how holographic technology can reshape teaching and training by introducing immersive, interactive, and highly engaging learning environments. The goal is to evaluate the potential of holograms to increase users' motivation, enhance understanding of complex subjects, and ultimately strengthen overall learning outcomes. Furthermore, it explores how holographic technology can "augment" lessons by enabling contributions from subject matter experts located anywhere in the world, eliminating the need for physical travel. Indeed, the underlying idea is that through holographic projection, institutions (such as the Civil Protection Agency) can bring global expertise directly into the classroom, promoting collaborative and enriched learning experiences without geographical constraints.

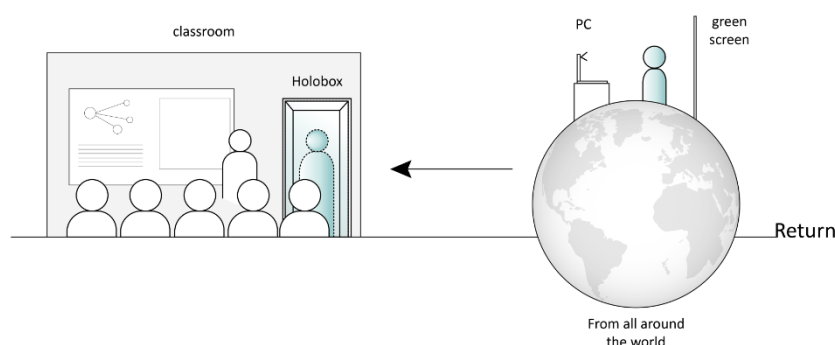


Figure 18: Augment lessons enabled by holographic technology

7.3.2 Methodological approach

The methodological approach adopted is grounded in a comprehensive review of the literature on the evolution of holography and its integration within educational contexts. This review is complemented by an analysis of immersive technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) which serve as synergistic tools to enhance holographic applications in teaching and training.

For more than a hundred years, holography has evolved as a dialogue between light and imagination. Its history is not a mere chronicle of inventions — it is a reservoir of ideas that challenges us to question, reinterpret, and expand the boundaries of reality in our future research.

- **1862:** John Henry Pepper's optical projection introduced 3D illusions.
- **1947:** Dennis Gabor formulated holography theory.
- **1960s–1980s:** Laser advancements enabled practical holograms.
- **2008–2016:** High-profile applications and devices like Microsoft HoloLens brought holography into mainstream technology. This progression underscores holography's interdisciplinary potential and its growing role in education.

This research is anchored by three pivotal questions that frame its scope and objectives, guiding the inquiry toward a deeper understanding of both theoretical foundations and practical implications.

- **(Q1)** What differences could holograms introduce to learning compared to conventional lessons?
- **(Q2)** What challenges do teachers/institutions encounter or anticipate when implementing holographic technologies, and what strategies can be employed to overcome these obstacles?

- **(Q3)** Which strategies and technology are most effective for integrating holographic interventions into traditional lectures, allowing expert to deliver targeted content from any geographical context?

(A1) This section provides an in-depth analysis of how holograms can transform learning experiences compared to traditional classroom methods. Holographic technology introduces several significant pedagogical differences when compared to traditional teaching methods. Conventional lessons typically rely on two-dimensional representations—such as textbooks, slides, and static diagrams—which often limit users' ability to visualize complex structures or dynamic processes. In contrast, holograms provide three-dimensional, spatially accurate representations that can be observed from multiple angles. This immersive visualization capability enhances cognitive processing by reducing abstraction, particularly in disciplines that involve intricate geometries or systems, such as engineering and architecture. Furthermore, holograms foster active learning by allowing users to promote experiential engagement rather than passive reception of information [1]. Research in educational psychology suggests that such interactive environments improve knowledge retention, conceptual understanding, and problem-solving skills [2]. Finally, holograms contribute to motivation and engagement by leveraging novelty and interactivity, which are critical factors in sustaining attention in modern classrooms. While traditional lessons often struggle to address diverse learning styles, holographic environments offer multimodal experiences that cater to visual and collaborative learners simultaneously.

(A2) The challenges that teachers encounter or anticipate when implementing holographic technologies, along with strategies to overcome them, are presented in this section. The integration of holographic technologies into educational environments presents several challenges that must be addressed to ensure effective adoption [3]. Technical complexity is among the most significant barriers; teachers often lack prior experience with advanced visualization systems, which can lead to difficulties in operating hardware and software platforms. This challenge is compounded by the need for specialized infrastructure, including high-performance projection systems and stable network connectivity, which may not be readily available in all institutions. Another critical issue is cost, as holographic equipment and maintenance require substantial financial investment. Limited budgets can hinder large-scale deployment, making affordability a key concern. Additionally, educators may face curricular integration challenges, as existing training plans are typically designed for traditional teaching methods and must be restructured to leverage holographic capabilities effectively.

To overcome these obstacles, several strategies can be implemented. First, comprehensive training programs should be developed to build technical proficiency and confidence in using holographic tools. Second, institutions can adopt phased implementation approaches, starting with pilot projects and shared holographic labs to evaluate feasibility and cost-effectiveness before full-scale adoption. Third, collaboration with technology providers and industry partners can help reduce costs through resource-sharing models and institutional partnerships.

(A3) Holographic projections offer a unique opportunity to allow experts to participate remotely without physical travel, creating global knowledge networks that transcend geographical barriers and promote real-time collaboration [4]. Such integration not only enhances accessibility but also supports inclusive and culturally diverse learning environments. By leveraging holographic telepresence, institutions can cultivate learning ecosystems that are immersive and globally connected.

7.3.3 Use case implementation

The adoption of 3D holographic technology in educational and professional contexts represents a transformative step toward immersive and interactive learning environments. At the university level, holograms enable real-time visualization of complex engineering structures - such as architectural models or infrastructural systems - enhancing spatial comprehension and supporting advanced design analysis.

Similarly, in the domain of public administration, holographic technology offers significant potential for the training of technical personnel responsible for infrastructure management, urban planning, and emergency response. Through holographic simulations, technicians can visualize and interact with complex systems - such as water networks, energy grids, or transportation infrastructures - in a risk-free environment. This approach facilitates scenario-based learning, improves decision-making skills, and supports the development of competencies aligned with smart city and digital twin paradigms.

To ensure effective implementation, **a multi-phase strategy is recommended**. Initial steps include pilot projects and the establishment of shared holographic laboratories accessible to both academic institutions and public agencies. Comprehensive training programs for educators and technical staff are essential to build digital literacy and operational proficiency. Finally, gradual integration into curricula and professional development frameworks - alongside complementary technologies such as Virtual Reality (VR) and Augmented Reality (AR) - will foster blended ecosystems that combine traditional instruction with cutting-edge visualization tools, promoting inclusivity, efficiency, and innovation in both education and public sector training.



Figure 19: Augment lessons with digital model display



Figure 20: Augment lessons with remote lecturer.

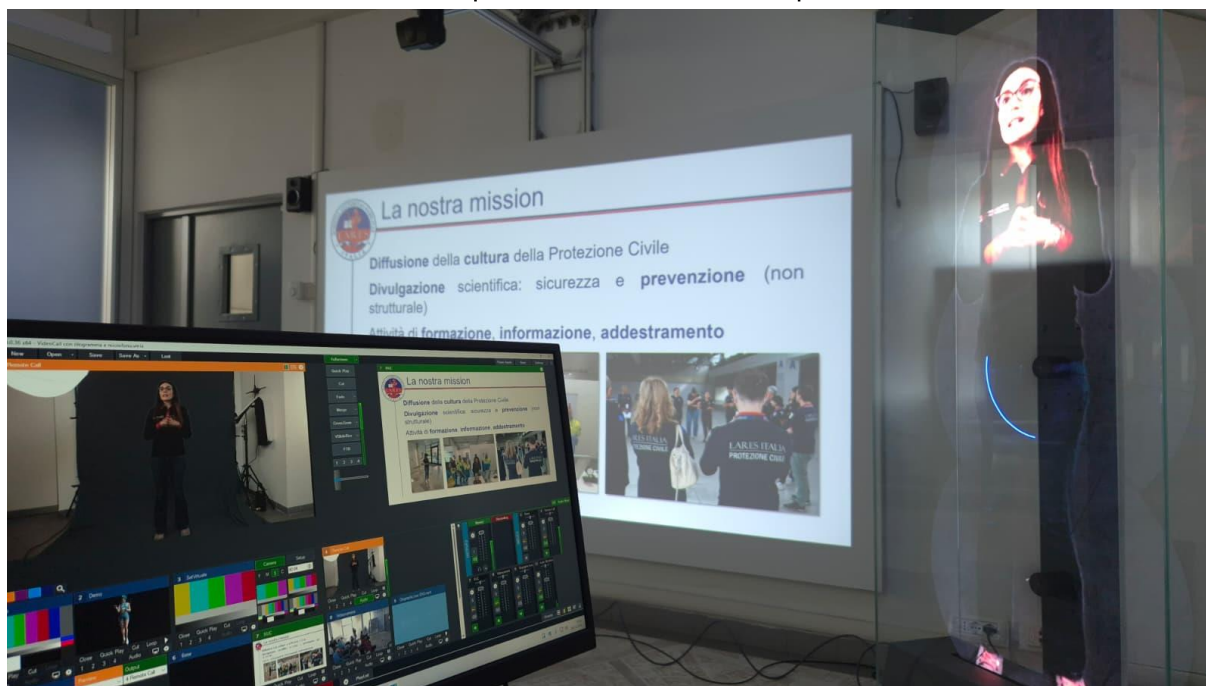


Figure 21: LARES involvement in the Master's Degree course "Conoscenza del Patrimonio costruito nell'epoca dei cambiamenti climatici" at Politecnico di Torino, supporting awareness-raising activities on territorial resilience for students.

7.3.4 Impact

The integration of holographic technology into educational settings offers substantial benefits. Empirical studies on immersive learning environments indicate that such technologies significantly increase users **engagement and motivation**, fostering active participation and sustained attention. Moreover, holographic visualization enhances **comprehension of abstract or complex concepts** by providing three-dimensional representations that support cognitive processing and spatial reasoning. These features also accommodate diverse learning styles, enabling multimodal interaction and promoting collaborative learning experiences.

From an institutional perspective, the adoption of holographic solutions positions educational organizations as innovators in 21st-century pedagogy, reinforcing their commitment to technological advancement and **global connectivity**. Immersive experiences facilitated by holograms encourage cultural awareness and inclusivity, creating opportunities for **cross-border collaboration** and exposure to international expertise without the constraints of physical mobility.

Looking ahead, the future trajectory of holographic education is closely linked to **emerging technologies** such as artificial intelligence and digital twins. AI-driven holographic tutors could provide personalized learning pathways, adaptive feedback, and real-time analytics, while integration with metaverse platforms may enable fully immersive, persistent learning environments. To validate these innovations, future longitudinal studies on knowledge retention, performance outcomes, and cognitive load will be essential, ensuring that the pedagogical effectiveness of holographic interventions is supported by robust empirical evidence.

8. Cross-Competence Development

8.1 Design Thinking for Asset Management Training

8.1.1 Objectives

In the context of PhD education, where the focus is on advancing knowledge and developing original solutions, integrating the Design Thinking can be instrumental in stimulating researchers' creativity and fostering the emergence of new ideas. This section describes a creative design experience aimed at developing effective innovative solutions for asset management workforce training, conducted in the third-level hard skills course "Digital Twin, Virtual Reality and Metaverse: technologies to support the asset management workforce" in within the Doctoral College of Civil and Environmental Engineering at Politecnico di Torino. The activity involved the participation of 10 Politecnico di Torino PhD students characterised by different levels of progression concerning their research path, i.e. attending cycles 38 to 40 and coming from different PhD programmes. The course attracted students' interest from the PhD programmes in Civil and Environmental Engineering, Electrical, Electronics, and Communications Engineering and Urban and Regional Development, as it addressed the topic of critical infrastructure management. The diverse backgrounds of the participants in engineering and architecture are valued as a strength for the activities, as they enable a broader and more stimulating multidisciplinary interaction, bringing in different skills, viewpoints, and experiences.



Figure 22: Third-level course experience

8.1.2 Methodological approach

The course was structured around the Design Thinking framework, alternating divergent and convergent thinking phases to explore both the problem space and the solution space. This framework allowed participants to identify, analyse, and address the complex challenges of asset management workforce training through iterative, human-centred and evidence-driven processes.

Step 1 – Introduction and Context Setting

The first session clarified objectives, introduced the participants and their research fields, and established the foundations for collaborative co-design activities. Recognising each participant's background was crucial to create the shared knowledge base required by Design Thinking methodologies, where each contributor becomes an active designer and co-creator.

Step 2 – Problem Definition

The initial focus is on the problem space empathy and definition. What was the initial situation? What was the problem with that situation? What problem do you want to solve? Why does this problem exist at all? What kind of problem is it? What are its different characteristics? What makes it a difficult problem to solve? What are the context conditions? Who were the stakeholders? What might have been done differently? These are just some of the questions that can guide us in examining the problem in depth, continuing to re-state, re-frame and redefine it according to different aspects in concrete and tangible terms. Problems formulated in a generic or abstract way hinder an understanding of the true nature of the negative aspect to be faced and, therefore, make it difficult or impossible to define the appropriate way to deal with it.

Through guided reflection, participants defined the training challenges in asset management using:

- Problem tree diagram: that helps to relate problems in a hierarchical order from bottom to top according to an analytical approach that makes explicit cause-effect relationships once the main one to start from has been defined. While this overview deconstructs and expands the problem, it also helps to better focus attention on a confined portion of the issues that can really be addressed through project objectives but with a broader overview that can determine their success. This step is crucial, although often overlooked or neglected, as it stimulates reflection on the relevance of research, directing it towards solutions that respond to actual, rather than abstract, threats. In the context of the challenge examined, for example, it emerged that issues related to asset management workforce training are of a varied nature and complexity. Although engineers were inclined to examine the pragmatic, technical, and technological aspects initially, it was immediately evident that there were multiple dimensions to be considered to determine the success of a possible project proposal. Training, in fact, should carefully consider the target audience it is aimed at, its characteristics, and the social, cultural and corporate context of reference. Therefore, the solution's user experience and feasibility are highly conditioned by aspects not directly linked to its technological quality.
- Stakeholder map technique: to force a visual representation and a clear understanding of all the actors involved or interested in a project, initiative or decision-making process. At this stage, researchers are asked to spend time carefully examining the problem, considering the different needs and viewpoints of the actors. Actors were clustered according to criteria such as their level of influence and interest in the problem. Asset management workforce training is a complex issue involving many stakeholders.
- SWOT analysis and system map techniques: to understand the interactions, dynamics, and interconnections between the different components of a complex system. Once the initial reasoning is summarised using the problem tree approach, the students are called upon to transform the diagram created by moving from each specific problem to a linked possible action.

All the mentioned activities are conducted by providing time for individual reflection, collective discussion and final individual reflection to stimulate participation and expression of everyone's opinion. This phase encouraged participants to recognise not only the technical, but also the social, organisational, and cultural dimensions of training design.

Step 3 – Observation and Technological Exploration

Students explored the potential of the most promising technologies that can be used in training activities, such as Augmented, Virtual, and Mixed Reality tools and Metaverse applications for workforce training. Through hands-on trials, participants experienced immersive systems and analysed state-of-the-art examples, discovering how technologies such as Digital Twins and AI can support experiential learning and simulation. Although this activity was time-consuming in organisational terms, it made it possible to overcome possible knowledge misalignments among the participants also due to their different backgrounds and knowledge. At the same time, participants are also encouraged to investigate the state-of-the-art applications of these technological solutions in related contexts or through replicable approaches. Each student approached the research according to their research interest and perspective. Consequently, the outputs were wide and varied providing further input to broaden or better define the Tree problem diagram. Studies dealing with literature reviews on the use of specific technologies and experiences developing virtual reality applications for activities in industrial and infrastructure contexts were reported. Other students focused, on the other hand, on the in-depth investigation of social and psychological aspects, finding reflections on the culture and age of workers and how technologies are introduced. Finally, the Operator 5.0 paradigm emerged as a new challenge, seeking greater resilience in systems based on the combination of user resilience and key enabling technologies. Sharing the experiences encountered energizes the following initial brainstorming on possible actions to be taken to achieve the objectives and enriches the individual's learning.

Step 4 – Ideation

Students are invited to brainstorm on the formulation of training solutions according to a divergent approach.

- **Analogy mapping:** to identify problems and solutions in one domain and apply them to another. This concept works by recognising relational similarities between things in different domains. For example, organisations need to invest in training to enable staff to develop and adapt like a gardener caring for plants to grow. Staff skills may wither or fail to adapt to change if attention is not paid (such as neglecting watering or pruning). Students were then asked to reflect on the opportunities derived from the analogies concerning asset management workforce training. The possible analogies were individually evaluated, shared and explained with the group and then collectively revised. Just as video games are a source of entertainment, technologies can help engage the user in educational and training contexts through a game approach. Alternatively, just as an orchestra must act in a synchronised manner in order to return a harmonious melody, workers must have a strong commitment from above in order to act cohesively. Starting from the three analogies rated most promising, the students concentrated on generating solutions exploiting strategies derived from other contexts. When some preliminary ideas begin to emerge, it is helpful to introduce techniques that stimulate the ideas through a series of questions and expand how they can be manipulated or developed.
- **SCAMPER list** has been illustrated as offering an organised, systematic and practical way to stimulate the imagination and is based on the idea that everything new comes from a modification of something that already exists. Each letter that makes up the acronym represents a word related to a question that must be asked to support the development of an idea or graft new solutions by playing with its characteristics. S means substitute and intends to replace one thing for another (e.g. parts, people, processes, materials, rules). C, combining one thing with another. A, adapt, doing something else (e.g. another purpose, role, function). M, modify something (e.g. the arrangement, the parts, the whole, the interactions, the cause, the effect). P, put to other use, use things for another purpose (e.g. the parts, the whole, the input, the output, use these in other applications, sectors). E, Eliminate something (e.g. parts, people, processes, materials, rules) R, reverse things. Within the ideation context, it is possible to assess the effectiveness of the creative process through four measures that take into account fluidity, i.e. the quantity of ideas produced, their flexibility in terms of variety and diversity, originality and their level of elaboration. The multitude of ideas that emerge must then be grouped, combined and reduced to begin formulating real solutions to the problem that can be designed in more detail.

Step 5 – Prototype

The teams proceeded to prototype their ideas, translating abstract concepts into tangible forms in order to collect feedback, validate assumptions, and refine their proposals. Among the different approaches introduced during the course, role-play prototyping was selected as the most effective method for this context. It is an active simulation technique that allows participants to quickly elicit the user experience of a product or service by enacting real-world interactions and observing behavioural responses. The collective scenario focused on designing a Virtual Reality learning platform based on interactive Digital Twin models of a hydropower infrastructure. The case study included training tasks for management and maintenance personnel, as well as an outreach component designed for community awareness and dissemination. To test the concept, the participants conducted a role-play simulation replicating a multi-stakeholder roundtable to evaluate the feasibility of the proposed training solution. Each PhD student impersonated one of the key stakeholders potentially affected by the project, including an IT developer, software designer, infrastructure engineer, operations manager, maintenance technician, HR representative, trade-union delegate, safety officer, and public-administration official. The diversity of roles, reflecting both public and private, internal and external perspectives, mirrored the Stakeholder Map developed in the earlier phase and ensured a wide range of viewpoints during the discussion. The instructor also participated, acting as the infrastructure concessionaire, guiding the debate and ensuring balanced consideration of all arguments. Following an initial presentation of the concept by the IT developer, the session evolved into a structured dialogue where multiple stakeholder perspectives converged. This exchange made it possible to identify divergent needs, conflicting priorities, and critical dependencies, while collaboratively analysing the strengths and weaknesses of the proposal. Feedback gathered in this phase informed a collective effort to refine and improve the prototype. The role-play exercise proved particularly effective for evaluating complex educational solutions, highlighting that focusing exclusively on technical performance can lead to shortcomings if economic, social, or cultural dimensions are neglected. As emerged from the earlier Problem Tree analysis, factors such as worker motivation, recognition of innovation-oriented behaviours, and the integration of training into professional certification processes are equally crucial for success. Overall, the collaborative and experiential setting fostered an atmosphere of creative and critical thinking, enabling participants to conceptualise training solutions that were both innovative and pragmatically grounded in real-world operational contexts.

Step 6 – Testing

Testing is the final stage of the design thinking process, where prototypes are presented to public users for feedback. In the course context, this phase corresponds to the experimentation that the individual participant is encouraged to do within their research field by exploiting the learned method. This prompt motivates them to continually refine their work to effectively respond to identified needs through a more structured and measurable approach.

Results

To collect feedback on the teaching approach adopted in the course, a questionnaire was administered to participants at the end of the final session. The results show a high level of appreciation for the structure and delivery of the activities, which fostered strong engagement and encouraged students to take an active role throughout the learning process. The use of Design Thinking was considered effective for addressing complex research problems, and students reported that they intend to adopt the methodology as part of their toolkit for future research challenges. Early-stage PhD students, in particular, highlighted its value in supporting exploration, problem-framing and the identification of alternative solution pathways. Among the techniques tested, 40% of participants identified the Problem Tree analysis as the most effective tool, while the remaining votes were distributed across the other methods. This finding confirms the need for a greater emphasis on problem definition in research processes and highlights the importance of avoiding premature convergence on solutions. At the same time, the absence of a dominant preference for the other techniques indicates that all contributed meaningfully to structuring and supporting the creative process. Regarding the specific challenge addressed, students recognised the strong potential of emerging technologies in training for the asset management workforce. Interactivity, customisation, game-based dynamics and collaborative features emerged as the most promising aspects for real-world implementation. The size of the group (10 students) was considered optimal, ensuring productive interaction with the instructor and among participants, and enabling the achievement of the planned objectives. However, it was

also noted that greater diversification of disciplinary backgrounds could enhance the divergent phases of the process - improving fluency, flexibility and originality of ideas - and support more sophisticated convergence towards robust and innovative solutions. In line with the analogy-mapping technique explored during the course, students highlighted how identifying relational similarities across domains can foster originality and promote connections between seemingly distant problems, enriching the ideation process. A further enhancement to the learning experience derived from the adoption of role-play prototyping, a method rarely used in conventional academic settings. By integrating visual, auditory and kinaesthetic dimensions, role-play simulations enabled participants to reproduce realistic professional scenarios and acquire practical competences. This experiential approach supported a deeper understanding of human dynamics, organisational behaviours and multi-stakeholder interactions. Moreover, it strengthened key transversal skills, including teamwork, communication, conflict management and leadership, within a safe environment that mirrors and anticipates real operational contexts.

8.1.3 Impact

The innovative learning framework exemplifies the transformative potential of combining Design Thinking with emerging digital technologies to advance asset management workforce training. The course experimentation not only aligns with current research trends but also reinforces the technology-transfer mission at the core of RETURN, bridging Education, Research and real-world operational needs. By integrating leading technologies a structured design methodology, the course demonstrates how technological innovation can be effectively transferred into training practices, enhancing the preparedness, awareness and adaptability of the future asset management workforce. The adoption of a Design Thinking approach promotes an educational model capable of enhancing creativity, divergent thinking, teamwork and empathy, while cultivating essential social and communication competencies, problem-framing, negotiation, active listening and the ability to integrate multiple perspectives into shared objectives. In this respect, the course operates as a technology-transfer laboratory, where doctoral students learn to convert technological opportunities into applicable, user-centred training solutions for complex socio-technical systems. Embedding Design Thinking in doctoral programmes thus serves as a catalyst for strengthening researchers' capability to respond to societal challenges through iterative, inclusive and human-centred innovation processes. The methodological framework experienced in the course has proven valid, replicable and scalable across educational, academic and professional contexts. Its adaptability makes it particularly well-suited for transfer to the RETURN project, where broader participation of stakeholders in the risk management and critical infrastructure fields will support the expansion of the Problem Tree analysis and the co-development of research prototypes with strategic impact for the asset management workforce.

A further consolidation of this technology-transfer trajectory occurred through the replication of the experience in an international Erasmus+ mobility context at a leading European technical university. The methodology was implemented with a new audience of researchers and practitioners, confirming its transferability across institutional and cultural environments. This international application also served as a European dissemination action for RETURN, showcasing how methodological innovation combined with advanced digital technologies can effectively support workforce development in the field of critical infrastructure asset management.

Overall, the experience confirms that embedding Design Thinking into advanced training pathways enhances research creativity, accelerates technology transfer, and increases societal impact—strengthening the integration between education, technological innovation and resilience within both the RETURN ecosystem and the wider European research landscape.

8.2 Knowledge Hub Platform

8.2.1 Objectives

The Knowledge Hub Platform serves as a comprehensive ecosystem supporting continuous skills development and knowledge management within complex organizational and institutional settings. It aims to foster upskilling and reskilling through personalized, adaptive learning paths aligned with evolving professional profiles and operational needs. The platform enhances organizational culture by encouraging collaboration, knowledge sharing, and multi-stakeholder engagement across different roles, disciplines, and geographic areas.

8.2.2 Methodological approach

The Knowledge Hub supports continuous skills development through a modular and scalable platform architecture that integrates tools for upskilling and reskilling. The training ecosystem is modular and provides access to structured courses, multimedia resources, and collaborative learning methods. It stays consistently aligned with the needs of different professional profiles.

The training section includes courses, webinars, interactive workshops, and e-learning modules organized by progressive levels of depth. Each item contains clear descriptions, multi-format materials, and assessment tests that support gradual learning. Users can obtain digital badges and recognized certifications. The catalog is continuously updated and combines internally developed content with resources from certified external providers, ensuring relevance to current regulations and emerging innovations.

To support the training process, the platform provides technical tutorials, operational guides, and microlearning content that promote the rapid acquisition of specific skills. Searching materials are facilitated by an indexing system that quickly identifies the content most relevant to the user's needs. The experience is further enhanced by a recommendation engine that suggests personalized courses based on the user's profile, previous experience, and identified training needs.

The environment includes collaborative spaces where users, experts, and institutional stakeholders can engage in thematic forums, communities of practice, multidisciplinary working groups, and participatory review activities. Multichannel messaging and notification systems facilitate the sharing of experiences and strengthen the organizational culture based on cooperation and professional growth.

A central element of the platform is Ragnarok, the intelligent system, integrated into the platform, that personalizes training paths and ensures continuous content updates.

The system provides an integrated, real-time updated course catalog covering both transversal skills and specialized technical expertise. Content may be internally developed or provided by certified external providers. The courses offer various levels of depth, personalized assessments, and digital badges for certifying acquired skills. This supports the enhancement of professional profiles and facilitates internal mobility across roles and functions.

Finally, integration with technical documentation and the institutional knowledge base allows users to contextualize training in real-world scenarios, connecting learning to the operational needs of the local area and the adoption of innovative methodologies, with a view to continuous improvement and responsible knowledge sharing.

Training Catalog

The central element of the training offering is the Training Catalog, a dynamic system with courses, webinars, interactive workshops, and e-learning modules organized by subject area, level, and user profile. Each content includes descriptive sheets, multi-format learning paths (videos, technical documents, tests), automatic assessments, and digital badges for certification. It also features an intelligent recommendation engine that suggests the most suitable learning paths based on existing skills and identified learning gaps. Content is continuously updated and integrated with certified external providers, keeping training aligned with new regulations and emerging technologies. Progress tracking dashboards provide visibility into results achieved and certifications acquired.

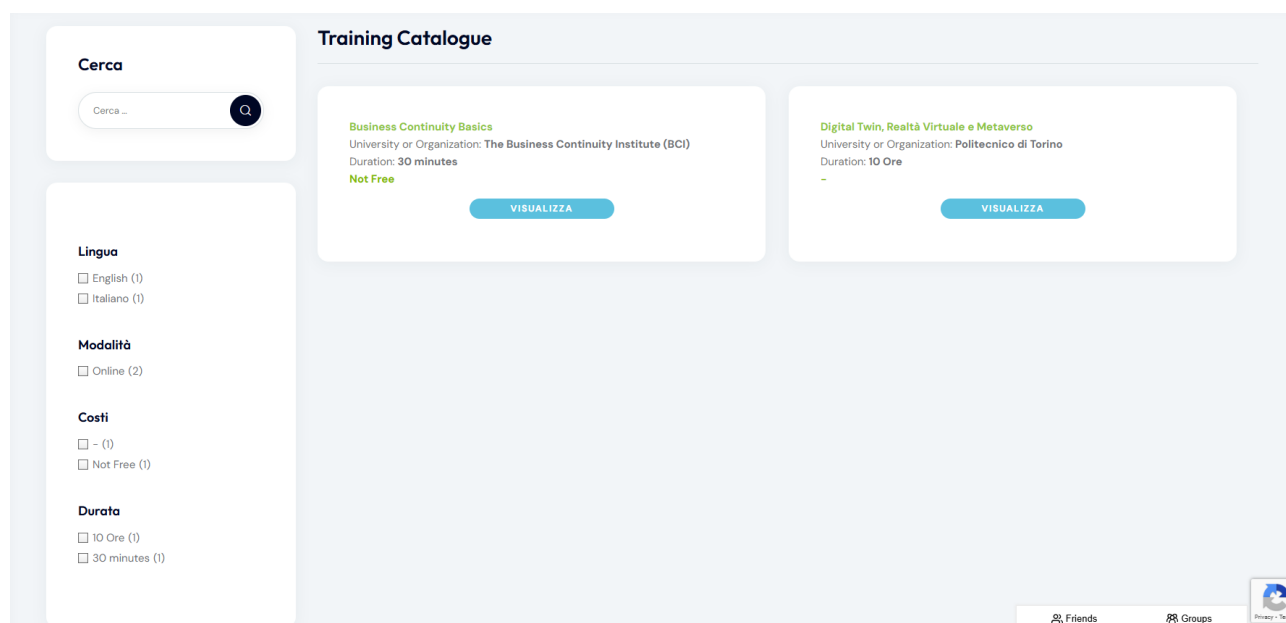


Figure 23: Training Catalog

Solutions and Knowledge Resources

The Solutions and Knowledge Resources section represents the platform's structured documentation hub. It includes technical and procedural documentation (manuals, SOPs, guidelines), interactive glossaries that ensure terminological consistency, and publications such as articles, case studies, and lessons learned. Documentation is semantically indexed, versioned, and open to contributions, comments, and revisions, enabling continuous improvement.

The platform fosters collaboration through thematic forums, communities of practice, multidisciplinary working groups, peer review spaces, and virtual mentorships. These are integrated with multichannel messaging and notification systems that facilitate the exchange of experiences between experts, junior staff, and institutional stakeholders, contributing to the strengthening of organizational culture and internal collaboration.

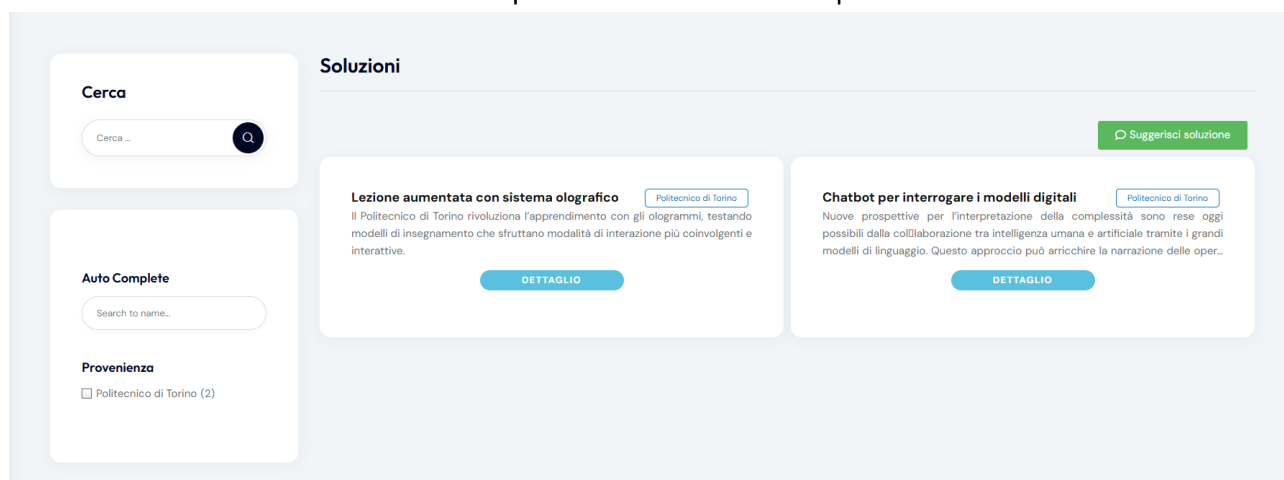


Figure 24: Solutions

Education Technology Glossary

The Education Technology Glossary section is a key element supporting the "Solutions" and "Training Catalog" areas. The RETURN Glossary (see Annex 2) provides a structured collection of technical terms, key concepts, and Project-specific definitions, offering users - professionals, operators, and citizens - an authoritative and easily accessible reference point. This tool allows for quick access to clear, contextualized explanations, avoiding interpretative ambiguities and ensuring consistent use of industry terminology.

The glossary therefore plays a cross-functional role, promoting consistency of concepts among users with different levels of experience, simplifying the understanding of training content and technical documentation, and providing immediate support during course use and resource consultation. Fully integrated with the Training Catalog and the Solutions section, it helps consolidate the Knowledge Hub as a comprehensive ecosystem, focused not only on training and documentation but also on ongoing support for navigating and assimilating professional and operational content. The Glossary is therefore an indispensable tool for ensuring clear, effective, and shared communication within the platform.

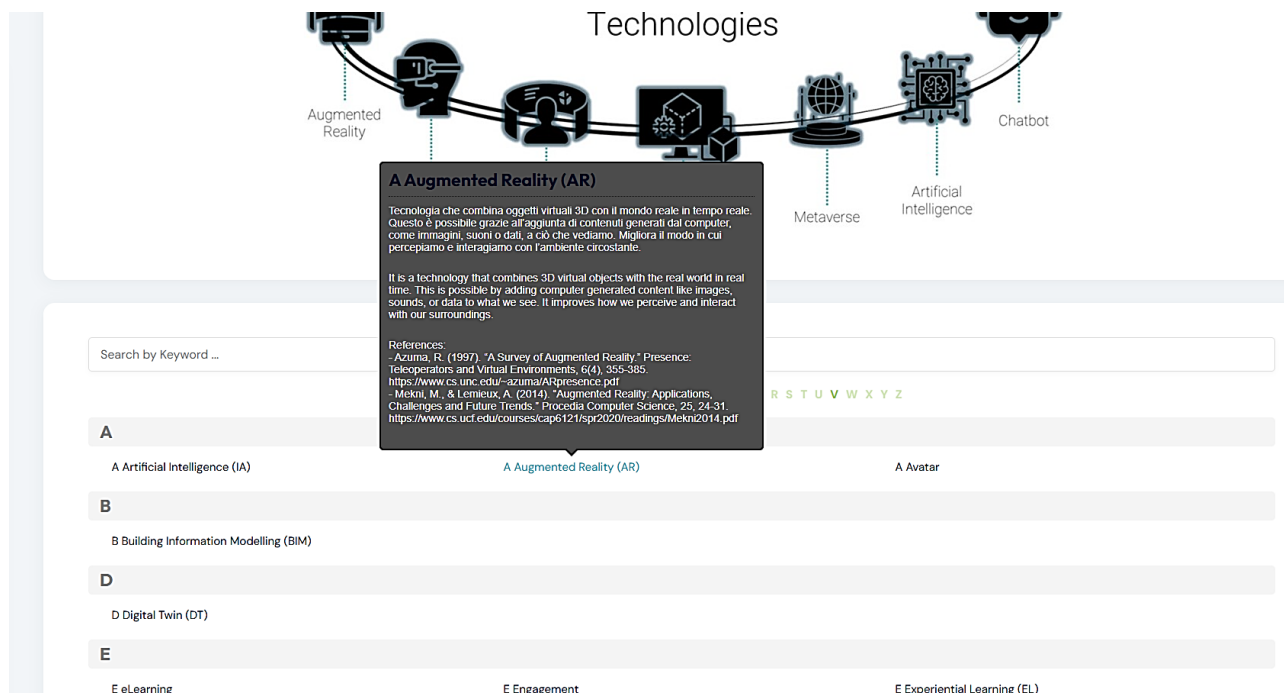


Figure 25: Education Technology Glossary

Overall, the glossary improves the quality of learning and interactions, promoting responsible knowledge management within the Knowledge Hub's institutional and professional community.

Smart Box

The Smart Box, as part of the platform's architecture, is a strategic tool supporting the expansion of knowledge and development of competencies. It enhances upskilling and reskilling processes through real-world, hands-on learning experiences and validation. By moving beyond a purely digital approach, the Smart Box acts as a territorial laboratory, allowing users to directly test the platform's features, acquire new skills, and validate their knowledge in environments marked by the complex interdependencies of critical infrastructure and natural phenomena.

The Catalogue component provides a centralized inventory of field data, analytical outputs, and supporting documentation, giving users access to practical training materials and up-to-date professional resources. The Explorer interface enables advanced geospatial data exploration, visualization, and scenario comparison, strengthening the ability to analyze territorial dynamics and system interactions.

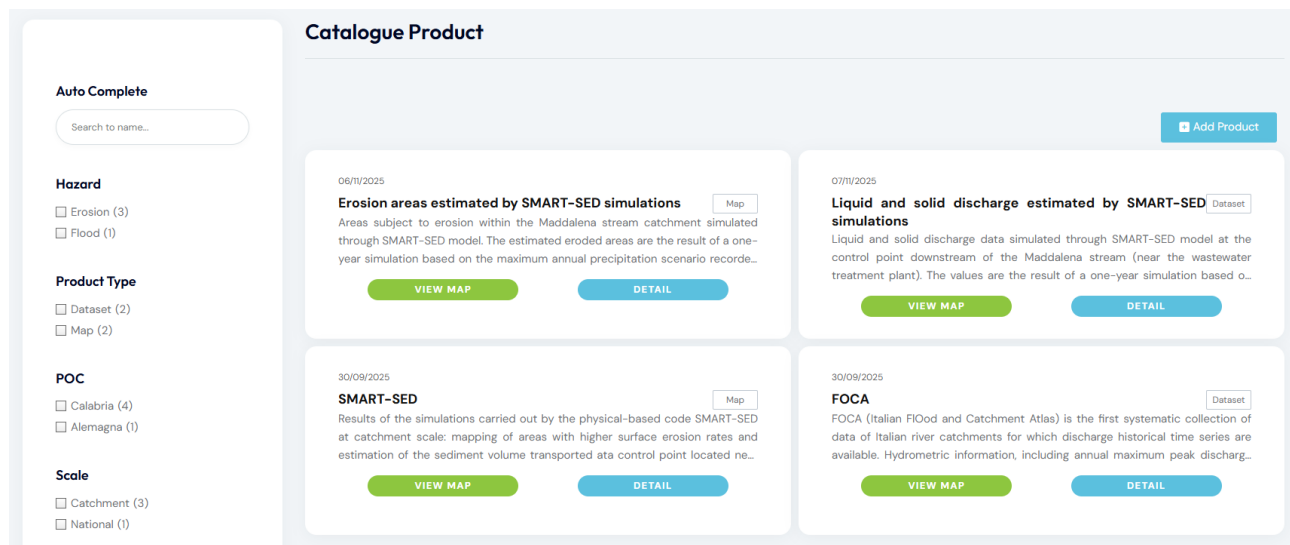
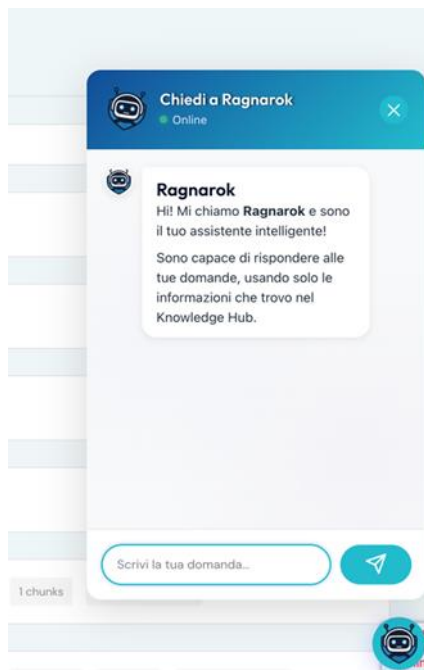


Figure 26: Catalogue Product of the Smart Box section

This architecture transforms the Smart Box into an active knowledge and skill development module—an “on the job” learning platform. It lets operators, technicians, and stakeholders gain hands-on expertise via mission-based monitoring, simulations, and real-world testing, enhancing analytical, technical, and problem-solving skills critical for managing strategic infrastructure. The distributed network of Smart Boxes across complex territories constantly feeds the institutional knowledge base with empirically validated data and case studies, creating ongoing opportunities for situational learning.

In summary, the Smart Box serves as an advanced support for organizational upskilling and reskilling, turning validated field information into immediately applicable skills and fostering a learning organization and increased resilience in high-impact operational contexts.

Ragnarok Technology



An innovative and distinctive feature of the platform is the integration of Ragnarok, an AI-driven system designed to optimize training processes and customize them based on user needs. Ragnarok enables the automatic generation of learning content, quizzes, and adaptive courses, supporting just-in-time learning and the use of content in microlearning mode. It also provides digital assistants capable of answering technical questions, guiding users through documentation, and providing personalized and ongoing support.

The system also facilitates the automatic updating of documentation, glossaries, and training materials, connecting internal and external sources to keep the knowledge base constantly aligned with regulations, standards, and emerging innovations. By analyzing user interactions, Ragnarok contributes to the review process with targeted suggestions and optimizes the recommendation engine by identifying content, courses, and thematic workgroups based on skills, interests, and platform usage behavior.

The integration of Ragnarok makes the Knowledge Hub an advanced learning environment, capable of offering highly personalized and proactive experiences, accelerating professional development processes and improving the resilience and competitiveness of the entire organization. Finally, the platform facilitates content management and sharing: experts can upload multimedia materials and documentation, while operators and citizens can access it to acquire knowledge, guided, when necessary, by AI suggestions that direct them to the training paths most relevant to their needs.

Ragnarok Documents Manager

636
TOTAL DOCUMENTS

569
PROCESSED

2567
TOTAL CHUNKS

2567
INDEXED CHUNKS

Documents List

ID	Title	Type	Chunks	Indexed	Status	Date	Actions
1648	Ragnarok	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1646	Analytics Survey	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1647	CI	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1645	Survey Test	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1644	Critical Infrastructure Protection in the Water Sector: A 2030 Outlook	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete

Figure 27: Ragnarok Documents Manager

Thanks to this intelligent and integrated architecture, the Knowledge Hub is a strategic tool for innovation in training and knowledge management. Its modularity and scalability make it suitable for diverse institutional and production contexts. It supports continuous skills growth and encourages responsible dissemination of knowledge within a complex community.

8.2.3 Impact

By combining digital resources, real-world experimentation, AI personalization, and collaborative knowledge exchange, the Knowledge Hub fosters professional development, internal mobility, and organizational resilience. It transforms training into an interactive, continuously evolving process that integrates formal education with practical application, enabling users to rapidly acquire and validate skills critical for managing complex systems and infrastructures. The platform also strengthens organizational cohesion by embedding a culture of cooperation, responsible knowledge sharing, and innovation-driven growth across institutional and production contexts.

In summary, reformulating the report by focusing on these elements aligns it with the platform's strategic purpose, methodological rigor, and transformative impact on professional competence and knowledge ecosystems. This approach underscores the Knowledge Hub as a cutting-edge tool for innovation in continuous learning and knowledge management.

9. The Resilient Operator concept

Digital transformation, increased systemic risks and the growing complexity of critical infrastructure require a redefinition of the role of professionals engaged in asset management. In this context, the figure of the Resilient Operator emerges: a worker who is not only capable of managing assets and processes, but also of adapting, learning, and reacting effectively to new challenges and work ecosystems. This concept resonates strongly with recent discussions on Construction 5.0 and Operator 5.0, where the evolution of industrial paradigms emphasizes human - centricity, sustainability, and resilience. The Resilient Operator can thus be interpreted as the critical infrastructure counterpart of Operator 5.0, embodying the fusion between human expertise and machine efficiency. In this vision, operators are no longer passive executors but active co - creators of resilient systems, able to collaborate with advanced technologies - digital twins, AI, IoT, and automation - while preserving the centrality of human judgment and adaptability. Recent literature also highlights that the COVID - 19 pandemic exposed the fragility of existing manufacturing and infrastructure systems, underscoring the workforce as both the most agile and most vulnerable resource. Making human operators more resilient - through training, education, and systemic support - becomes the cornerstone of building organizations capable of withstanding disruptions. The Resilient Operator 5.0 paradigm, developed in the context of Industry 5.0, demonstrates how resilience must be framed not only at the technological or systemic level, but also at the human one, strengthening cognitive, emotional, and collaborative dimensions alongside technical expertise. Within the critical infrastructure domain, the Resilient Operator thus emerges as a new professional paradigm, bridging tradition and innovation, and combining established technical skills with the flexibility, agility, and cross - domain awareness required by today's contexts. Their training and development represent the most advanced outcome of reskilling and upskilling programmes supported by Education Technology.

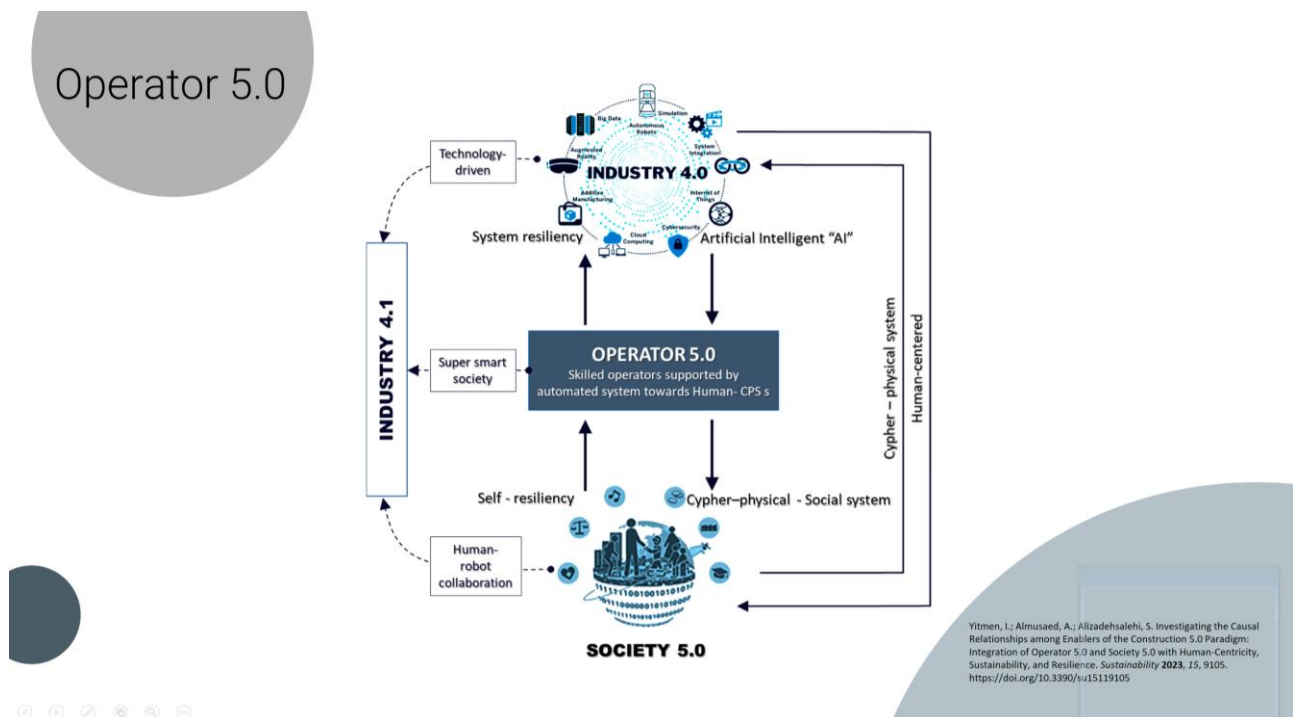


Figure 28: Operator 5.0 paradigm

Resilient Operator

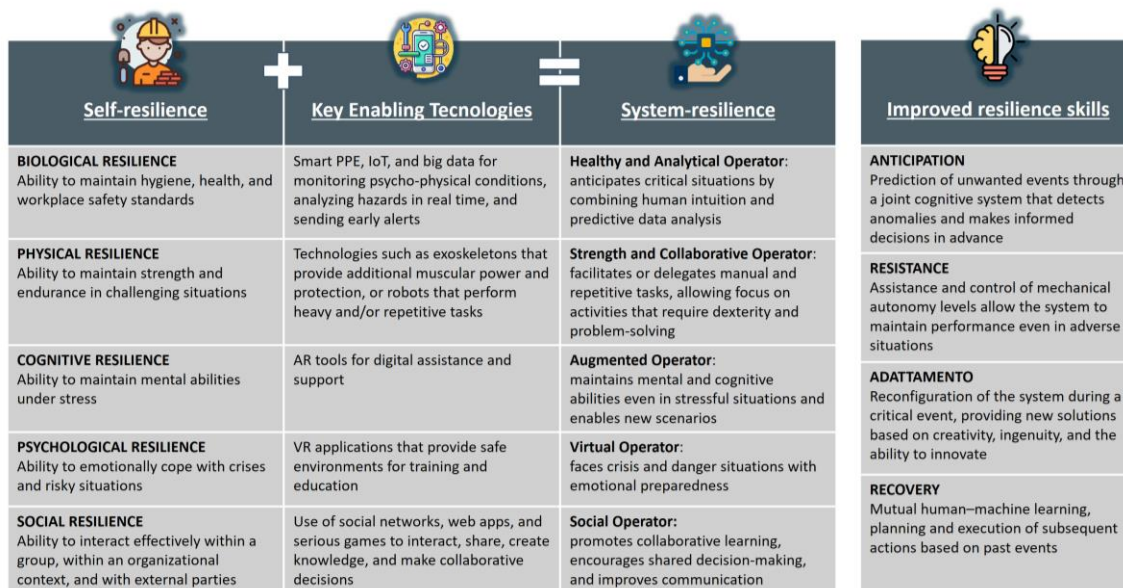


Figure 29: Operator 5.0 skills

10. Conclusions

This deliverable has presented a coordinated set of technological and methodological solutions aimed at advancing the re-skilling and up-skilling of the critical infrastructure workforce. The development of multiple innovative tools demonstrates how advanced Educational Technologies can elevate experiential learning, strengthen procedural reliability, and improve operational situational awareness. The Knowledge Hub Platform consolidates these efforts by offering an integrated, scalable environment that supports continuous learning, structured knowledge exchange, and AI-enabled training guidance. Collectively, the activities conducted define a coherent and forward-looking framework for modernising workforce development in the critical infrastructure domain, enabling the emergence of competent, adaptive, and resilient professionals capable of operating effectively within increasingly complex socio-technical systems.

11. Annexes

- **Annex A:** Rethinking Education on Critical Infrastructure Resilience and risk management: Insights from a Systematic Review
- **Annex B:** Knowledge Hub Glossary of Technologies

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multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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1. Technical references

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RE = Restricted to a group specified by the consortium (including the Commission Services)

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2. ABSTRACT

The rapid advancement of digital technologies, combined with the growing complexity of infrastructure systems and their exposure to multi-hazard risks, is profoundly transforming the skills required of personnel involved in the management of critical infrastructures. In this context, Task T6.5 – Re-skilling and Up-skilling of the Asset Management Workforce focuses on exploring the most promising innovative technologies to promote digital, multidisciplinary, and sustainable training for the asset management workforce involved in the operation of Critical Infrastructures. This deliverable describes the methodologies and digital tools adopted to enhance workforce training, leveraging advanced Educational Technologies (EdTech) and updated pedagogical approaches. It reports on the implementation and evaluation of three technological prototypes: (i) a natural language chatbot for OpenBIM data interaction, (ii) an immersive Virtual Reality serious game for operational and inspection training, and (iii) a holographic-based learning environment, demonstrating how digital tools can support experiential, context-aware, and scalable learning pathways. The document also describes cross-competence development activities grounded in Design Thinking, which foster creativity, problem-framing capabilities, and user-centred solution design.

Furthermore, the deliverable introduces the architecture of an integrated Knowledge Hub Platform, a modular environment that consolidates training resources, technical documentation, collaborative spaces, and AI-driven support systems to enable continuous upskilling and knowledge sharing. Collectively, these components contribute to the development of the Resilient Operator, a professional capable of interacting effectively with digital infrastructures, adapting to evolving operational scenarios, and supporting organisational resilience.

Overall, the deliverable outlines methodological, technological, and organisational insights for designing next-generation training solutions aimed at strengthening the preparedness and competence of the critical infrastructure workforce.

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4. Introduction

Critical infrastructures (CIs) constitute the essential operational layer of contemporary societies. Their continuity is fundamental to economic stability, population safety and the functioning of interconnected socio-technical systems. Increasing interdependencies among infrastructure networks, combined with exposure to natural, technological and hybrid hazards, have significantly amplified systemic vulnerability. Emerging stressors such as climate-change-induced extremes, cyberattacks, supply chain instability and geopolitical disruptions highlight the need to strengthen both technical robustness and human-centred operational resilience.

Within this scenario, Asset Management (AM) has evolved into a strategic function integrating performance optimisation, lifecycle planning, safety management and sustainability objectives. The digitalisation of infrastructures, driven by Artificial Intelligence (AI), the Internet of Things (IoT), pervasive sensing, automation, Big Data analytics and Digital Twins (DTs), has fundamentally reshaped operational workflows. Advanced monitoring, predictive maintenance and real-time diagnostics improve situational awareness but simultaneously introduce new layers of complexity that require updated professional competencies.

This technological transition is generating a widening skills gap across infrastructure-intensive organisations. Operators, engineers and maintenance personnel are increasingly required to interpret heterogeneous data streams, interact with digital models, coordinate across multi-disciplinary processes and operate effectively under uncertainty. Capabilities such as data literacy, systems thinking, adaptive decision-making and cross-domain communication are becoming as critical as traditional engineering expertise.

Consequently, workforce development must evolve beyond conventional training paradigms based on classroom teaching and procedural instruction. Contemporary operational environments require active, simulation-based and experiential learning models capable of replicating the temporal, spatial and cognitive demands of real infrastructure operations. Over the last two decades, pedagogical approaches such as problem-based learning, design thinking, scenario-based training and reflective practice have been recognised as effective for enhancing analytical skills, collaborative behaviours and resilience-oriented reasoning.

In this context, Educational Technologies (EdTech) provide enabling mechanisms for the modernisation of training processes. EdTech encompasses a spectrum of digital solutions—Learning Management Systems (LMS), mobile learning applications, AI-driven tutoring systems, serious games, holographic interfaces, and immersive environments such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). When applied to infrastructure management, these technologies support the creation of controlled, repeatable and risk-free environments for practising inspection routines, emergency response procedures, asset-maintenance workflows and multi-actor coordination tasks. Furthermore, data-driven platforms allow the integration of performance analytics, adaptive feedback and personalised learning paths.

The increasing availability of BIM-based models, sensor-generated datasets, and real-time operational information strengthens the potential of simulation-based and XR-enabled training ecosystems. Digital Twins and XR platforms enable multi-scenario simulations with high levels of fidelity, supporting the development of situational awareness, error recognition, procedural accuracy and decision-making under stress. Training therefore becomes an iterative process where users operate within virtualised replicas of real assets, receive immediate feedback and progressively consolidate their competencies.

Parallel developments in industrial and construction paradigms such as Industry 5.0 and Construction 5.0 underscore the need for human-centric, resilient and technologically augmented operators. This evolution frames the concept of the Resilient Operator: a professional capable of interacting with intelligent systems, adapting to dynamic operational conditions and ensuring service continuity across complex infrastructure environments.

5. Stakeholder mapping

Understanding who constitutes the asset management workforce is a fundamental step in designing effective training strategies for the governance and operation of Critical Infrastructures (CIs). To this end, a stakeholder mapping exercise was conducted—developed in synergy with the activities of TS3—to identify the actors involved across the entire infrastructure value chain. The resulting representation highlights the breadth and heterogeneity of the ecosystem, which encompasses a wide range of public and private entities operating at different spatial, organisational and operational levels.

Critical Infrastructure Operators and Technical Workforce. This group includes asset managers, operations personnel, engineers, maintenance teams, safety managers, and training managers. They constitute the operational core of infrastructure systems, ensuring day-to-day functionality, service continuity, and the execution of monitoring, diagnostics, intervention, and maintenance activities throughout the asset lifecycle.

Training needs and digital skills:

- Advanced understanding of digital twins, BIM/OpenBIM models, and IoT-enabled monitoring systems
- Data literacy for interpreting sensor data, dashboards, and predictive analytics
- Competence with automated and AI-assisted diagnostic tools
- Use of digital platforms for asset lifecycle management, maintenance planning, and incident reporting
- Simulation-based training for operational procedures and risk scenarios

Governance, Regulatory and Oversight Bodies. This category comprises regulatory authorities, public administrations, inspection agencies, and institutions responsible for setting standards, overseeing safety, and ensuring regulatory compliance. They play a strategic role in multi-level coordination, risk management, and long-term infrastructural planning.

Training needs and digital skills:

- Understanding of digital governance frameworks, cyber-physical risk, and data-driven regulation
- Skills in using decision-support tools, GIS platforms, and multi-risk assessment systems
- Ability to interpret large-scale infrastructure datasets and compliance dashboards
- Familiarity with simulation tools for scenario planning and policy testing
- Knowledge of digital auditing, traceability systems, and automated reporting workflows

Emergency-Management and Public-Safety Organisations. This group includes Civil Protection agencies, Fire Department, State Police, Medical Rescue, Carabinieri Force, and other response organisations. They operate across preparedness, response, and recovery phases, intervening in high-complexity scenarios that require interagency coordination, rapid decision-making, and the ability to act under pressure.

Training needs and digital skills:

- Use of real-time information systems, command-and-control platforms, and geospatial tools
- XR-based simulation training (VR/AR/MR) for emergency scenarios, evacuation, and hazardous environments
- Competence in drone operations, remote sensing, and digital field-reporting tools
- Data literacy for validating and acting upon real-time alerts, sensor streams, and predictive hazard models
- Ability to operate interoperable communication systems across agencies and infrastructure operators
- Cyber awareness, especially during events involving cascading cyber-physical impacts

Education, Training and Certification Ecosystem. This cluster encompasses universities, vocational training centres, instructors, professional trainers, and certification bodies. It supports continuous workforce development and prepares future generations entering the infrastructure sector, thereby influencing the quality, evolution, and long-term sustainability of professional competencies.

Training needs and digital skills:

- Capacity to design digitally enabled, multidisciplinary training pathways aligned with emerging technologies
- Familiarity with EdTech tools such as LMS platforms, serious games, and VR/AR training modules
- Competence in developing digital assessments, microcredentials, and skills certification systems
- Ability to integrate real infrastructure datasets, digital twins, and simulation environments into curricula
- Knowledge of instructional design methodologies suitable for complex socio-technical systems

The stakeholder map represented in the figure clearly illustrates the systemic dimension of the challenge: the resilience of critical infrastructures depends on the coordinated action of a wide plurality of actors, each bringing specific responsibilities, knowledge domains and operational constraints. The interaction between these groups highlights the need for transversal competences, shared situational awareness and interoperable training solutions capable of bridging organisational boundaries.

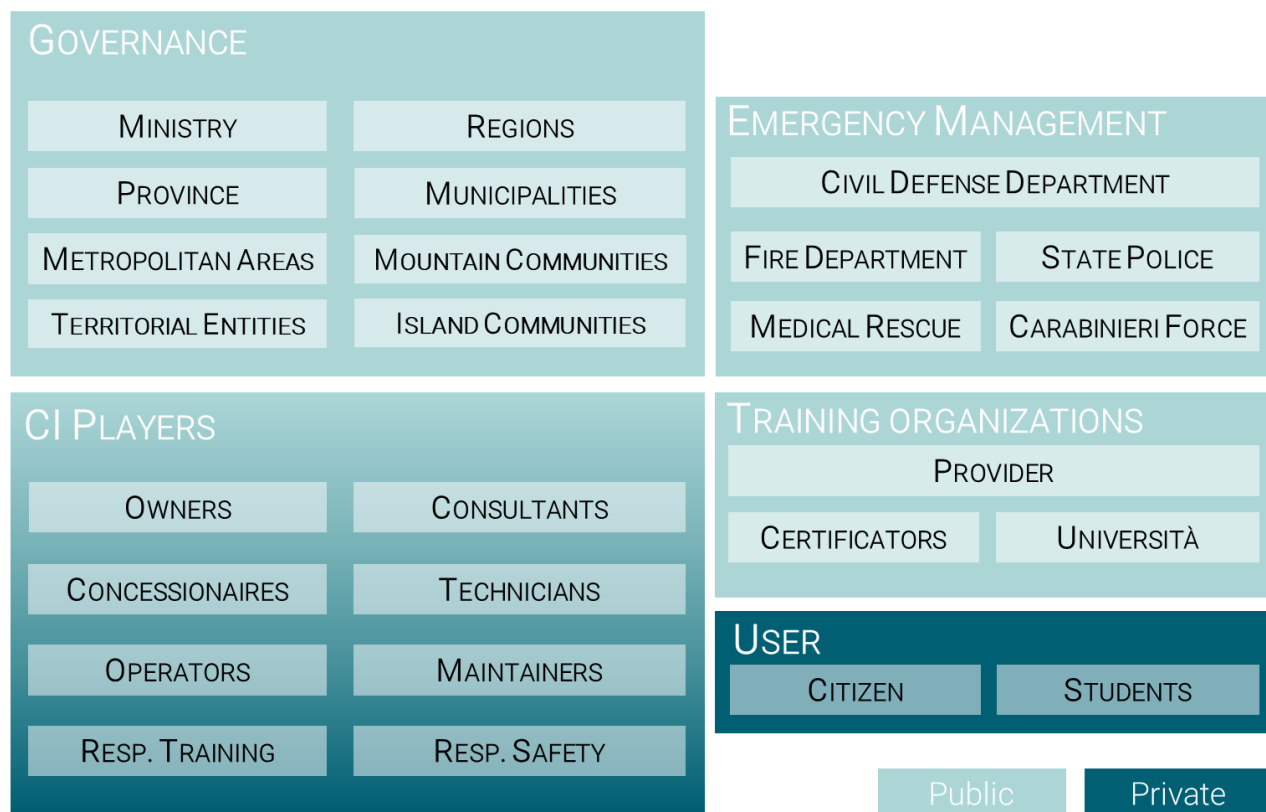


Figure 1: Asset management workforce stakeholder map

The topic of training is inherently complex and positioned at the intersection of multiple macro-systems: the built environment and critical infrastructure, the natural environment in which these assets are embedded, and the emergency-management domain. This overarching system must continuously respond to immediate shocks—such as natural hazard events—as well as to long-term pressures including climate change, urbanisation, economic crises, and other systemic stressors.

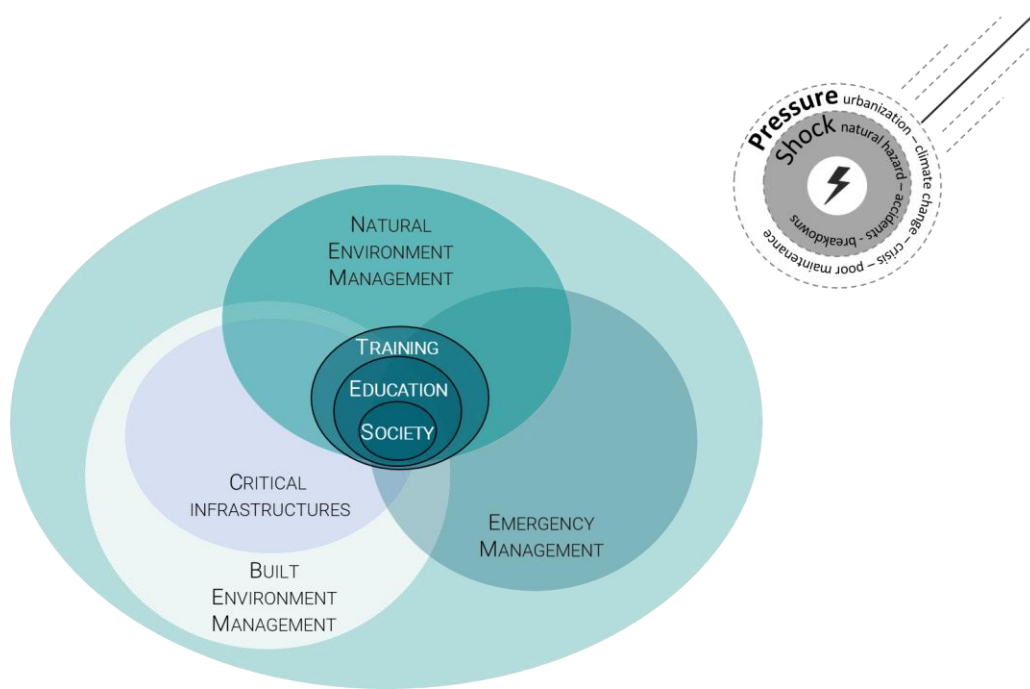


Figure 2: System map of the training problem space

6. Education Technology

The digital transformation of critical infrastructures is reshaping the skills required of their management and operational personnel. Within this framework, Education Technology (EdTech) plays a central role in fostering re-skilling and up-skilling processes, enabling adaptive, data-driven, and experiential forms of learning.

EdTech integrates a variety of tools - ranging from immersive environments and simulation systems to AI-driven adaptive platforms - that enhance both technical competence and situational awareness in complex operational contexts.

To ground the RETURN project's training activities in a solid scientific foundation, this section draws upon the outcomes of the systematic review entitled "*Rethinking Education on Critical Infrastructure Resilience and Risk Management: Insights from a Systematic Review*" (see [Annex 1](#)). This review provides a comprehensive synthesis of current approaches, identifying emerging technologies and methodological trends that can improve the performance, capability, and awareness of personnel involved in the management of critical infrastructures. The systematic review analyses more than a decade of international research exploring how digital, cognitive, and immersive technologies can support professional development in high-risk and data-intensive environments. The findings highlight several key methodological and technological domains relevant to the RETURN framework.

7. Practical Implementations and Experimentation

7.1 Chatbot

7.1.1 Objectives

The increasing complexity of digital models and data environments in critical infrastructure management calls for new interfaces that facilitate intuitive and meaningful access to information. The collaboration between human intelligence and Artificial Intelligence (AI), enabled by Large Language Models (LLMs), introduces new perspectives for interpreting this complexity. LLMs enhance the narrative, semantic richness, and accessibility of digital models, transforming them into intelligible representations that can be explored even by non-expert users in the field.

This pilot explores the use of a chatbot as a cognitive interpretation tool capable of improving understanding and knowledge extraction from Building Information Modelling (BIM) data systems. Within the context of a CI, the chatbot acts both as a training assistant and as an intelligent knowledge interface enabling users to query and navigate complex OpenBIM datasets through natural language. The overall objective is to foster data accessibility, knowledge retention, and training efficiency for personnel engaged in asset management and maintenance, thus bridging the gap between digital complexity and human operational practice.

7.1.2 Methodological approach

The operational workflow is designed to enable bidirectional communication between the user and the BIM information models enriched with data relevant to the management and maintenance of critical infrastructures. The chatbot acts as a semantic interpreter, translating natural language requests into executable commands within the digital model environment.

Operational Flow

1. The user formulates a query in natural language (e.g., “Select all pipes” or “Show me elements with parameter level equal to 0”).
2. The chatbot interprets and classifies the request using Natural Language Processing (NLP) techniques, identifying the user’s intent and relevant entities.
3. The chatbot sends the corresponding command to the BIM environment through API-based communication, triggering the appropriate Python function within Blender.
4. The BIM software executes the requested operation, for instance, filtering or selecting specific objects, and displays the results in the viewer for immediate visual feedback.

This workflow establishes a natural-language interface to access both graphical and alphanumeric information, effectively transforming the BIM model into an interactive digital knowledge base.

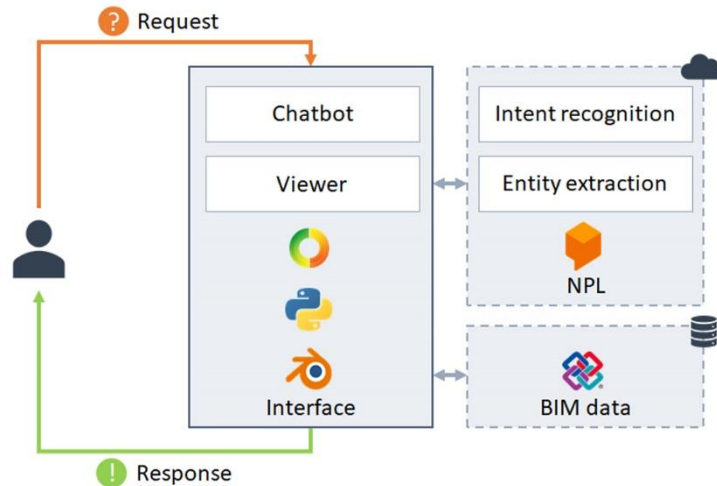


Figure 3: Architecture of the technical solution

System Architecture

The System Architecture consists of two main components.

- **Chatbot Interface:** Responsible for managing the communication between the user and the BIM software. It employs NLP technologies for Intent Recognition and Entity Extraction, using dedicated APIs to interact with the BIM database and perform data-driven operations. for Intent Recognition and Entity Extraction.
- **3D Viewer:** Enables the real-time visualisation of the BIM model within the same interface. This component supports intuitive exploration of both visual and informational data, reinforcing the cognitive link between model geometry and metadata.

Software Tools and Data Workflow

The digital model was authored in Autodesk Revit 2024, selected because it is one of the most widely used BIM authoring tools in the architecture, engineering, and construction (AEC) industry and therefore ensures high interoperability and compatibility with other platforms and workflows. The model was then exported in IFC4 format to guarantee full OpenBIM data exchange and long-term accessibility across different software ecosystems.

For model interaction, Blender 4.2 was adopted with the Bonsai add-on (developed by IfcOpenShell), as it offers extensive capabilities for rendering, animation, simulation, and the manipulation of complex 3D geometries within a single workspace.

Communication between Blender and the chatbot is handled by a custom plugin developed in Python, which integrates a chatbot created in Dialogflow. This plugin enables seamless API communication between the NLP module and the 3D environment, allowing the execution of contextual functions such as element selection, filtering, or counting.

The first step is to design the NLP module in Dialogflow through the creation of *Intents* and *Entities*, following best practices described in Amershi et al. (2019) to ensure a smooth and natural conversational experience.

- **Entities** were defined to enrich intent understanding and identify target data in user queries.

They are realised according to the context of the domain in which they are used and must be associated with a specific intent. As a non-exhaustive example, the Entity Class used in the Intent 'Class_Selection' to select objects based on their IFC class is shown. The aim is to make the virtual assistant recognise IFC classes by synonyms. For example, we want the class IfcPipeSegment to be recognised by entering the word 'pipe' to facilitate conversation. Consequently, the agent reacts to the sentence 'select all the door' by correctly identifying the Intent and recognising the parameter 'class' equal to 'IfcDoor'.

Class

Entity	Synonyms
IfcWindow	Finestra, Windows, Window, IfcWindows, Finestre
IfcDoor	Porta, Door, IfcDoor, Porte
IfcWall	IfcWall, Muri, Muro, Wall, Walls
IfcSlab	IfcSlab, floor, pavement, covering
IfcPipeSegment	IfcPipeSegment, pipe
IfcPipeFitting	IfcPipeSegment, pipe
IfcValve	
IfcRoof	

Agent

USER SAYS: select all the doot

DEFAULT RESPONSE: I have select the IfcDoor

INTENT: Class_Selection

ACTION: Not available

PARAMETER	VALUE
seleziona	select
class	IfcDoor

SENTIMENT: Query Score: 0.0

DIAGNOSTIC INFO

Figure 4: Example of setting up Entities on Dialogflow

- Intents were configured to trigger specific functions once a user's request was correctly classified.

Their definition included: (i) the configuration of training phrases for NLP classification; (ii) the insertion of multiple Entities to create the parameters required for API calls; (iii) and a testing phase to validate the chatbot's responses. For instance, the intent `Select_byParameterValue` was set to identify both the parameter name and its value in a request such as "Show me the elements with parameter level equal to 0", recognising "level" as the parameter and "0" as the value.

Select_byPamameterValue

Training phrases

Template phrases are deprecated and will be ignored in training time. More details here.

When a user says something similar to a training phrase, Dialogflow matches it to the intent. You don't have to create an exhaustive list. Dialogflow will fill out the list with similar expressions. To extract parameter values, use annotations with available system or custom entity types.

95 Add user expression

95 please, highlight the objects with parameter class equal to Wall

95 can you select all the object with parameter date equal to today?

95 all elements with parameter Installation equal to 06/05/2024

95 all elements with parameter type equal to type1

95 Select elements with parameter WBS equal to 00_00

95 Select elements with parameter WBS equal to 00_00

Action and parameters

Enter action name

REQUIRED	PARAMETER NAME	ENTITY	VALUE	IS LIST
☐	name	@Parameter	\$name	☐
☐	value	@value	\$value	☐
☐	Enter name	Enter entity	Enter value	☐

Agent

USER SAYS: show me the element with parameter level equal to 0

INTENT: Select_byPamameterValue

ACTION: Not available

PARAMETER	VALUE
value	0
name	level

SENTIMENT: Query Score: -

Figure 5: Example of Intent setting on Dialogflow

The integration of the NLP module with the Blender interface takes place through the use of the Scripting section of the program, allowing the execution of Python scripts that communicate via API with the Dialogflow server. Once the BIM data were imported in IFC format, specific functions could be executed thanks to Intent and Entity recognition, leveraging the IfcOpenShell libraries to access and manipulate model information directly. This configuration establishes a closed-loop interaction where natural-language input, data interpretation, and 3D visual feedback coexist in real time, enabling operators and trainees to engage with complex infrastructure data in an accessible, immersive, and learning-oriented environment.

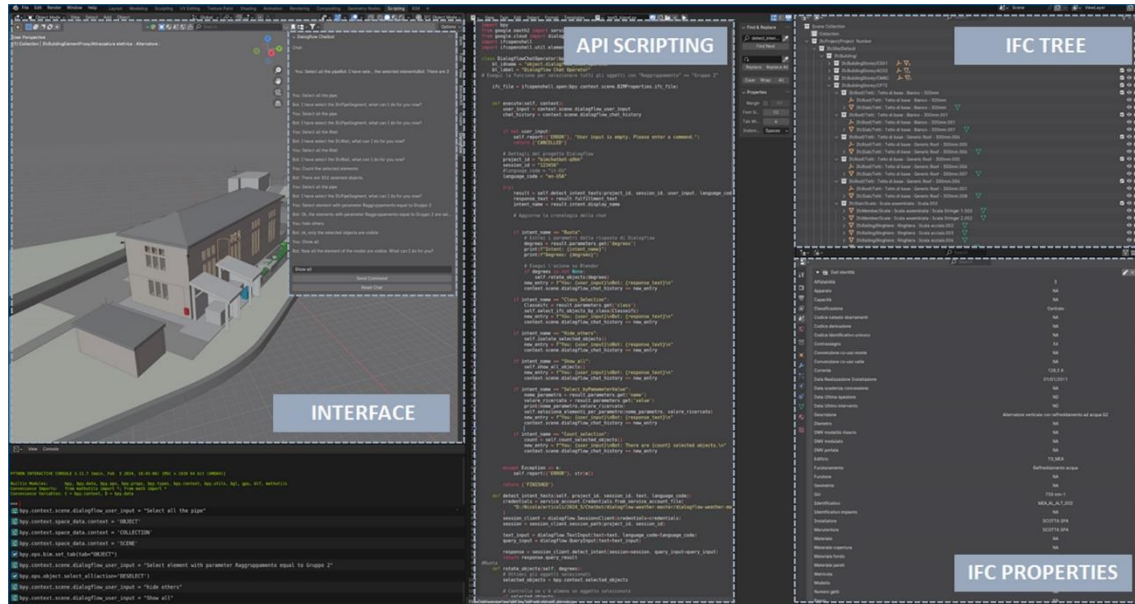


Figure 6: Blender Scripting interface for prototype development

7.1.3 Use case implementation

The architecture of the technical solution described above was implemented through an actual case study to validate the approach. The realised prototype aims to query the graphic and alphanumeric database resulting from a standardised digitalisation process of a large hydroelectric power plant park. The chatbot fulfils the need to access the complex structure of the BIM database and intuitively, even by non-expert personnel, to consult the master data of the main components making up the plants for management and maintenance purposes.



Figure 7: Meano hydroelectric power station in Pomaretto (TO) used as a case study



Figure 8: Workflow implementation of the case study

Autodesk Revit 2024 was used as BIM authoring software. Subsequently, it was exported in IFC4 format and imported into Blender 4.2 via the Add-on Bonsai9, developed by IfcOpenShell and available free online. The Python programming language makes it possible to link Dialogflow with specific Blender functions via API, such as selecting or counting elements via natural language. Once the workflow has been established, it is possible to talk to the chatbot to send requests to the Dialogflow agent.

A series of explanatory use cases are proposed for:

- The identification of items, either by class – e.g., all pipes or concerning the value of a specific parameter – electrical and mechanical equipment, which are about the same electrical production group.

At the start of the conversation, the chatbot tells the user what he can do; simultaneously, the Blender interface shows the IFC model (Fig. 9, point 1). Next, the user is asked to select ‘pipe’ elements. By recognising the Intent ‘Class_Selection’, a script can select elements with the required IFC class (Fig. 9, point 2), as previously described. To facilitate the identification of the elements of interest, the user asks to hide the other objects (Fig. 9, point 3), and the chatbot executes the script associated with the specific Intent. The conversation continues with the user requesting to select the objects by value, requesting the Intent ‘Select_byParameterValue’ by specifying the parameter name ‘Grouping’ (Fig. 11, point 4) and the value ‘Group 2’ (Fig. 9, point 5).

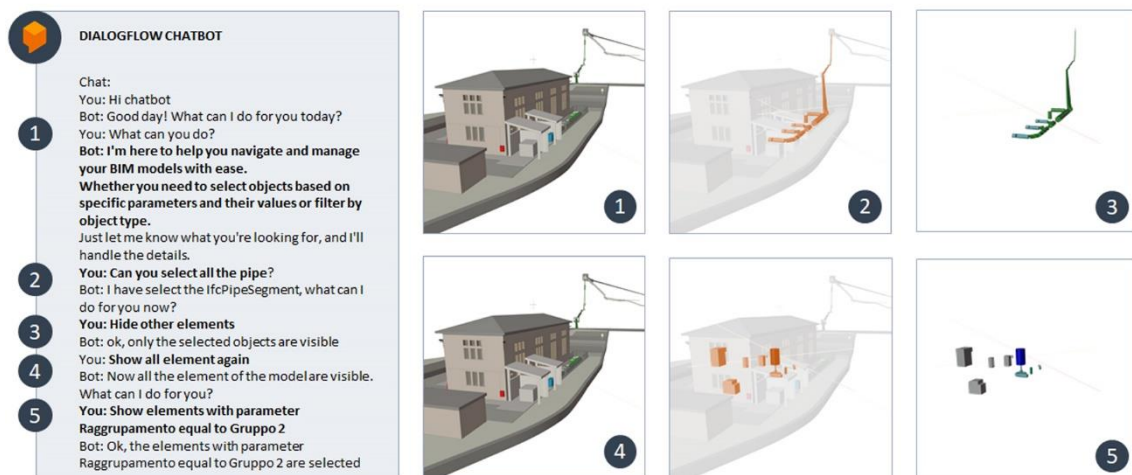


Figure 9: Example of conversation with natural language element selection

- b) The counting of items with specific characteristics, such as the equipment maintained by a particular person on a specific date.

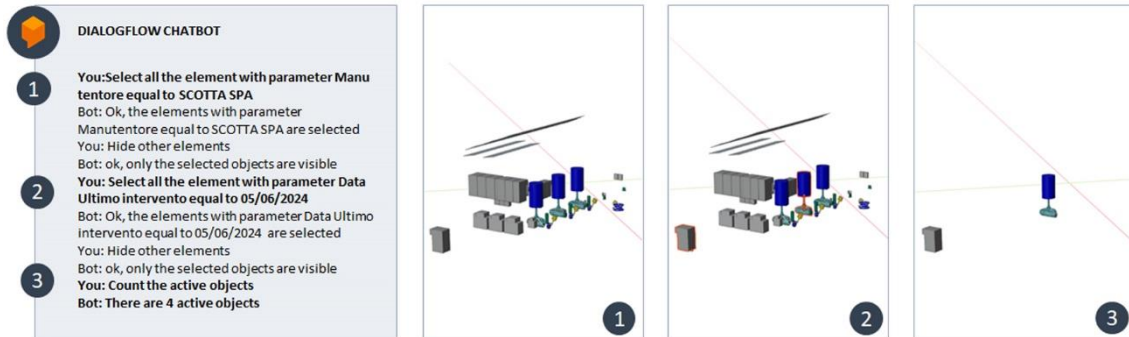


Figure 10: Example of conversation with natural language element counting

7.1.4 Impact

The chatbot prototype demonstrated the feasibility of integrating NLP and AI interfaces with OpenBIM environments for both training and operational purposes in the context of critical infrastructures.

This experimentation confirms that AI-assisted interaction can provide a valuable educational and operational tool for asset management personnel, bridging the gap between complex digital models and human understanding. Main results and benefits:

- Improved data accessibility: even non-specialist users can easily retrieve technical information without navigating complex modelling software or database interfaces.
- Enhanced learning and cognitive retention: the conversational approach supports experiential and contextual learning, promoting active knowledge acquisition.
- Scalability and interoperability: the framework can be adapted to other infrastructure typologies—such as water networks, energy grids, and transport systems—thanks to its OpenBIM-based architecture.
- Increased workforce capability: by simplifying the access to technical and maintenance data, the system contributes to up-skilling and re-skilling of operators, aligning training processes with the goals of the RETURN project.

7.2 Serious game

7.2.1 Objectives

The increasing structural and operational complexity of critical infrastructures requires training solutions capable of supporting accurate system comprehension, risk awareness, and procedural reliability. Literature in the fields of human-machine interaction, immersive simulation, and safety engineering highlights the effectiveness of Virtual Reality Serious Games (VR-SGs) in reproducing hazardous or restricted environments and in enabling controlled, repeatable training conditions.

The objective of this prototype is to evaluate the feasibility and effectiveness of an immersive VR Serious Game as a technical training tool for complex infrastructural systems. The prototype is designed to consolidate heterogeneous technical content, such as operational procedures, safety protocols, and process documentation, into a unified, interactive simulation environment that replicates real operational scenarios.

The overarching goal is to foster intuitive comprehension of infrastructure processes, strengthen users' ability to recognise risks and operational conditions, and improve training effectiveness for diverse user profiles, ranging from non-expert visitors to professional operators. Immersive environments are used to support safe exploration and contextualised guidance, aligning training content and difficulty with the needs of critical-infrastructure management.

7.2.2 Methodological approach

The methodological approach is grounded in the integration of immersive simulation, digital modelling, and interaction-driven training strategies. The prototype adopts a multi-layer framework combining:

- **Virtual Reality** technologies to reproduce spatial conditions, operational sequences, and restricted-access zones in a safe and controlled manner.
- **Building Information Modelling** for the geometric and semantic representation of infrastructural assets, ensuring consistency between virtual and real operational environments.
- Interactive procedural modelling, enabling the encoding of standard operating procedures, risk categories, and maintenance workflows into dynamic, executable training scenarios.
- **AI**-supported interaction modules, based on Large Language Models (LLMs), to facilitate context-aware guidance, adaptive feedback, and advanced information retrieval during training sessions.

The methodology focuses on translating heterogeneous technical content into structured digital workflows. Scenario design follows a task-oriented approach, mapping each operational activity onto a sequence of verifiable user interactions. This approach allows for monitoring user performance, validating procedural compliance, and ensuring fidelity between training dynamics and real operational practices.

This combination allows the creation of realistic scenarios enriched with procedures, safety information, operational actions and simulations. The approach replaces traditional static learning methods—such as manuals and supervised visits—with dynamic experiences that enhance comprehension, engagement, and decision-making capabilities.

System Architecture

The architecture is based on a multilayer pipeline that integrates heterogeneous data sources, digital models, interaction systems, and intelligent services. Its goal is to transform technical and documentary information into a navigable virtual environment that is consistent with the real infrastructure and equipped with advanced user-support functionalities.

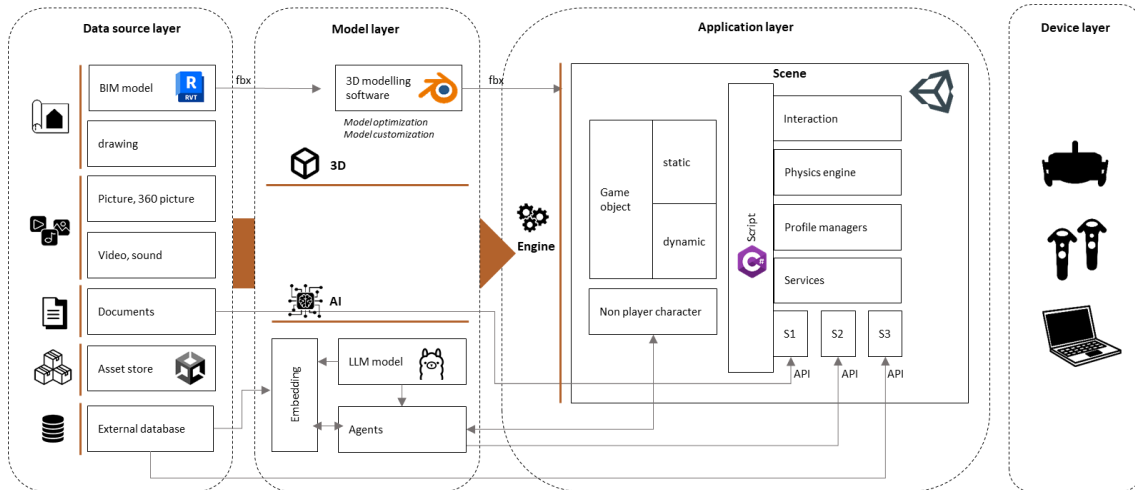


Figure 11: System architecture

The **Data Source Layer** gathers all the inputs required to feed the system. The BIM model of the critical infrastructure, developed in Autodesk Revit 2024, provides the geometric and informational foundation of the virtual environment and serves as the primary source for generating the 3D assets used in the simulation. Alongside the BIM-derived data, multimedia materials such as audio descriptions, operational videos, and 360° panoramic images contribute realistic and contextual references. Technical documentation—manuals, procedures, safety guidelines, and risk registers—as well as structured information from operational databases, supplies the content required for knowledge retrieval and AI-based guidance. External asset-store resources further enrich the scene by providing additional graphical elements and objects not included in the original BIM model.

The **Model Layer** handles the transformation of raw input data into assets and structures that can be directly used within the game engine. The BIM model exported from Autodesk Revit 2024 is imported into a 3D modelling software such as Blender, where it undergoes mesh cleaning, reduction, topology adjustments, texture remapping, and material refinement to ensure performance and visual coherence in real-time rendering. Additional scene elements, such as signage, indicators, props, and character models, are created or enhanced in this layer to support the narrative and functional requirements of the immersive experience. This workflow ensures that a BIM model originally conceived for design and documentation becomes a performant and visually coherent asset suitable for VR environments. In parallel, the Model Layer manages the preparation of the content required for knowledge-retrieval functionalities and orchestrates the AI-driven processes that interface with these contents. Technical documents, safety manuals, procedures, as well as structured information coming from internal or external databases, are segmented into smaller units and converted into vector embeddings, which are then stored in a semantic database such as ChromaDB. A retrieval pipeline based on LangChain orchestrates semantic search over this database and forwards the most relevant passages to the language model when queried by the user. A local language model, executed through Ollama, is also instantiated in this layer, forming the computational basis for AI-assisted guidance and contextual interpretation and enabling the system to dynamically access and interpret both documents and database records.

The **Application Layer** is responsible for orchestrating the runtime behaviour of the immersive serious game and integrates all components that enable scene composition, user interaction, and intelligent services. In this layer, the assets produced in the Model Layer are instantiated as game objects within the game engine, where they acquire the visual, physical, and behavioural properties required for execution. The scene is constructed by placing BIM-derived models, props, non-player characters, and multimedia elements into a coherent spatial layout. The environment is configured with materials, colliders, animations, lighting, spatial audio, and environmental effects to ensure consistency and navigability. Once the scene is assembled, C# scripts define the behaviour of the system. These scripts handle user interactions, such as activating points of interest, navigating the environment, or triggering procedural steps, as well as physics, collisions, role-based logic, and validation of operational actions. Through this scripting layer, the environment becomes reactive, operationally meaningful, and capable of supporting task-based learning. The Application Layer also integrates external and intelligent services through dedicated API calls. C# scripts communicate with local or remote endpoints to retrieve data, trigger functionalities, or update contextual information. AI-driven queries are routed to the semantic search and LLM components described in the Model Layer, allowing the system to provide context-aware explanations and adaptive guidance directly within the VR environment.

The **Device Layer** defines the hardware configuration through which the immersive serious game is executed and experienced. It includes all the physical components responsible for running the application, rendering the environment, and enabling user interaction within the virtual space. At the core of this layer is the computer workstation, which provides the computational resources required to execute the game engine, render the 3D environment, and manage the AI-driven services accessed through API calls. The performance of the workstation, particularly its GPU, CPU, and RAM, directly influences the fluidity of the immersive experience, the fidelity of real-time rendering, and the responsiveness of user interactions. User engagement with the virtual environment is enabled through VR head-mounted displays (HMDs), which provide stereoscopic rendering, head-tracking capabilities, and an immersive field of view that reproduces the scale and spatial characteristics of the infrastructure being simulated. The HMD ensures spatial presence and allows users to perceive depth, distance, and environmental cues consistent with real-world operations. Interaction within the VR environment is further supported by handheld controllers, which allow users to navigate, select objects, activate interactive elements, and perform actions associated with training procedures. The controllers' tracking systems translate hand gestures and movements into in-world interactions, enabling precise manipulation of objects, activation of scripts, and execution of task sequences. Combined, these devices establish the physical interface between the user and the application, ensuring that the immersive training environment is not only visually coherent but also operationally usable, responsive, and aligned with the functional demands of critical-infrastructure training.

7.2.3 Use case implementation

The Safety & Operations Training Hub (SOTH) serves as the demonstrative use case for evaluating the potential of immersive technologies in the context of critical-infrastructure training. The prototype has been developed around the simulation of a wastewater treatment plant, where articulated processes, restricted operational areas, and multiple risk categories are only partially conveyed through manuals, technical documentation, and supervised site visits. SOTH addresses these limitations through an experiential design approach that integrates narrative, interactivity, and advanced digital technologies. By immersing users in a virtual representation of the plant enriched with information, procedures, actions, and simulated scenarios, the system enables safe exploration of complex processes and supports the development of decision-making skills without exposing operators to real hazards. The prototype has been conceived as an immersive, role-based training environment capable of supporting both educational exploration and operational training. It leverages BIM-derived models for geometric accuracy, VR technologies for spatial immersion, and AI-driven interactions based on Large Language Models to provide contextual guidance. This integration makes it possible to transform procedural manuals, safety documents, and risk registers into adaptive, context-aware instructions tailored to the user's role and position within the plant.



Figure 12: Safety & Operations Training Hub

The training experience is structured around three user profiles, each with specific objectives and interaction modes:

- **Visitor profile**

This profile targets non-expert users approaching the plant for educational or outreach purposes. The system offers a guided narrative pathway that introduces the main components of the wastewater treatment process—from the screening unit to final disinfection—and provides access to both the water line and the sludge line. Interactive elements such as dynamic illustrations, highlighted components, animations, and audio-guided explanations help users understand process flows and regulatory requirements concerning effluent quality. The focus for this profile is on accessibility, intuitive comprehension, and general awareness.

- **Operator profile**

Technical operators require a deeper understanding of operational procedures, equipment behaviour, and safety practices. For this profile, SOTH simulates control, monitoring, and maintenance tasks through interactive checklists and task-based scenarios. Users can inspect parameters, identify anomalies, and access video-guided procedures illustrating correct interventions. The simulation also presents the main operational hazards, biological risks from aerosols and microorganisms, explosion risks from biogas in anaerobic digesters, and chemical risks related to corrosive substances, supported by animations, hazard indicators, and informational panels. The objective is to strengthen procedural adherence, situational awareness, and safe decision-making.

- **Inspector profile**

The inspector profile is designed for users responsible for assessment, verification, and compliance monitoring. This mode allows users to navigate the plant with access to inspection-specific tools, such as system overviews, risk maps, documentation linking, and contextual queries supported by the integrated AI mechanisms. Inspectors can review operational conditions, verify that procedures are followed correctly, examine safety-related information, and assess plant conformity with regulatory requirements. This profile focuses on analytical capabilities, risk identification, and the evaluation of safety measures within the virtual environment.

Within this use case, the Safety & Operations Training Hub operates explicitly as a serious game in which the wastewater treatment plant becomes a playable environment for infrastructure training. The three profiles described above are interpreted as distinct ways of engaging with the same virtual plant, each associated with different objectives, tools, and evaluation criteria. Visitors focus on process understanding and general awareness, operators on execution and monitoring of procedures, and inspectors on verification and documentation of safety conditions. The learner overview figure “Learner specifics” visualises this structure by presenting the three profiles as separate entry points that share a common spatial and information backbone while accessing different layers of interaction and feedback.

This role-based framing ensures continuity with the methodological approach. The same BIM-derived geometry, interactive procedures, and AI-assisted information services are reused across profiles, but filtered according to the responsibilities and permissions associated with each role. In practice, this means that the serious game does not create three different worlds, but a single virtual infrastructure that supports multiple training perspectives.



Figure 13: Learner specifics

The temporal organisation of the serious game, summarised in the “Storyline” figure, defines each session as a mission with a clear beginning, middle, and end. A single-entry scene establishes the configuration of the run; from there, the story branches into three normal-operation paths that correspond to the water line, the sludge line, or a combined full path; these paths can be temporarily diverted into sudden-hazard episodes; and all trajectories converge in a common debriefing scene. In this way, the figure encodes the overall rhythm of the game configuration, exposure to the process under normal conditions, optional disruption through hazards, and structured closure without yet detailing what happens in each scene, which is addressed in the subsequent figures.

The same storyline is shared by all three user profiles and by the main hazard families, which are mapped alongside the flow. This makes the figure a compact representation of how the methodological choices are operationalised in practice: task-oriented interactions are grouped into coherent missions along the water or sludge line; hazard simulations are attached to those missions rather than treated as isolated events; and the final debriefing provides a stable place where performance across runs, roles, and risk types can be compared. The “Storyline” diagram therefore functions less as a list of scenes and more as a structural template that organises how scenarios are composed, repeated, and evaluated within the overall training platform.

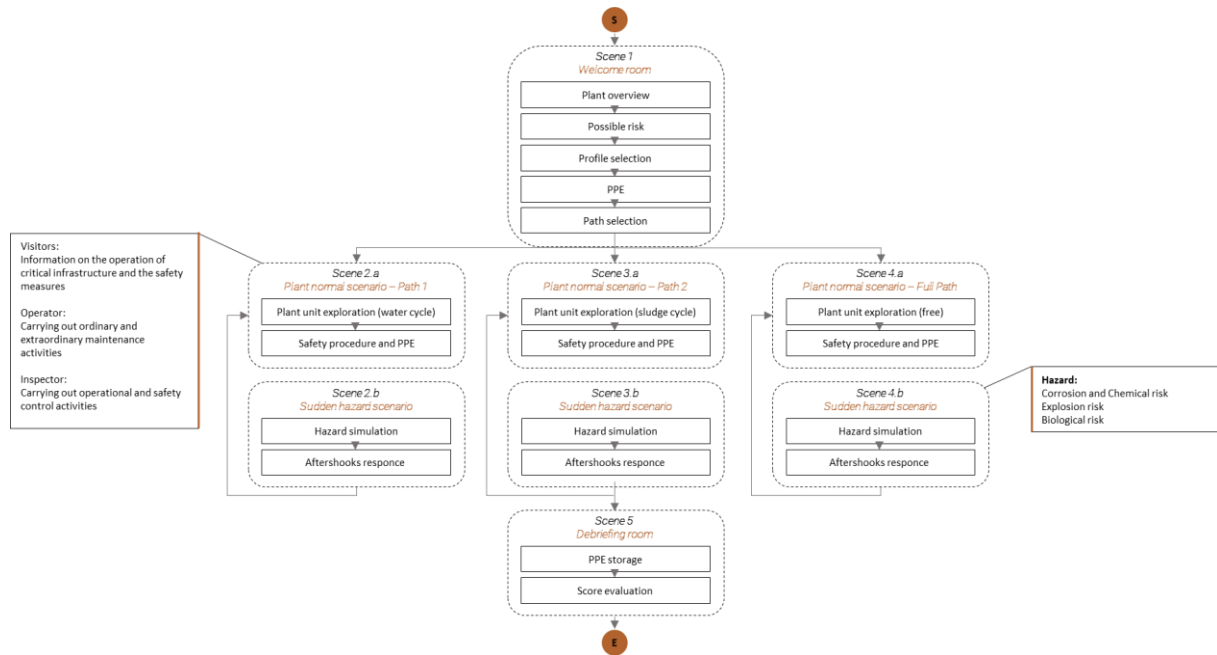


Figure 14: Storyline

The Welcome room is the first scene in which the serious game becomes concrete for the user. As shown in the dedicated figure, the space is structured into five functional areas: plant overview, infrastructure-related risks, profile selection, personal protective equipment (PPE), and path selection. In the plant overview area, a simplified representation of the wastewater treatment process introduces the main units and highlights the relation between water and sludge paths. The risk area recalls the main hazard categories relevant for the plant, aligning the immersive scenario with the risk taxonomy used in documentation and risk registers.

In the profile selection area, users confirm the visitor, operator, or inspector mode, linking the abstract learner types to an actual game configuration. The PPE area recalls mandatory equipment for the chosen role and, where relevant, for the selected path, reinforcing the connection between digital training and real safety requirements. Finally, the path selection area at number 5, allows users to choose between the water, sludge, or full plant trajectories defined in the storyline.

Welcome room

- 1 Plant overview
- 2 Infrastructure-related risks
- 3 Profile selection
- 4 Personal Protective Equipment
- 5 Path selection



Figure 15: Welcome room

Path

Challenges

- Maintenance activity
- Equipment movement
- Fluid dynamics
- LLM integration

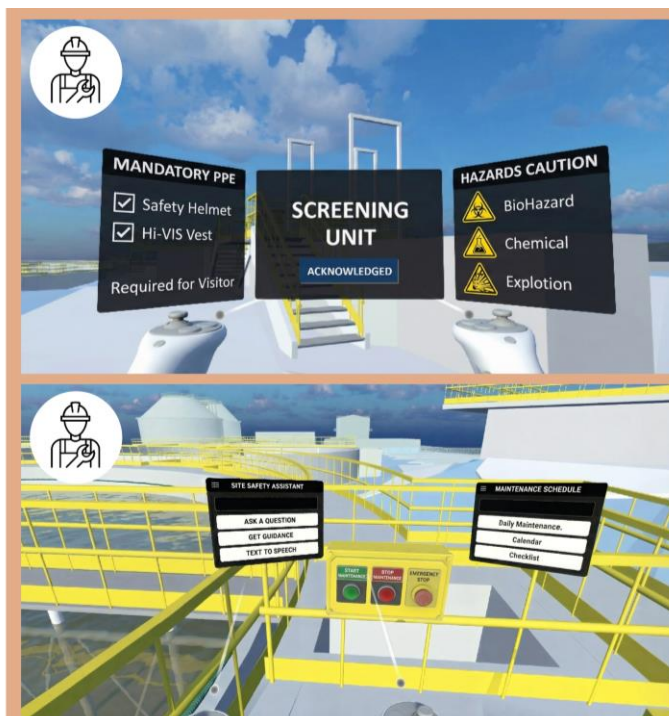


Figure 16: Operator interactions within the screening unit of the water treatment line

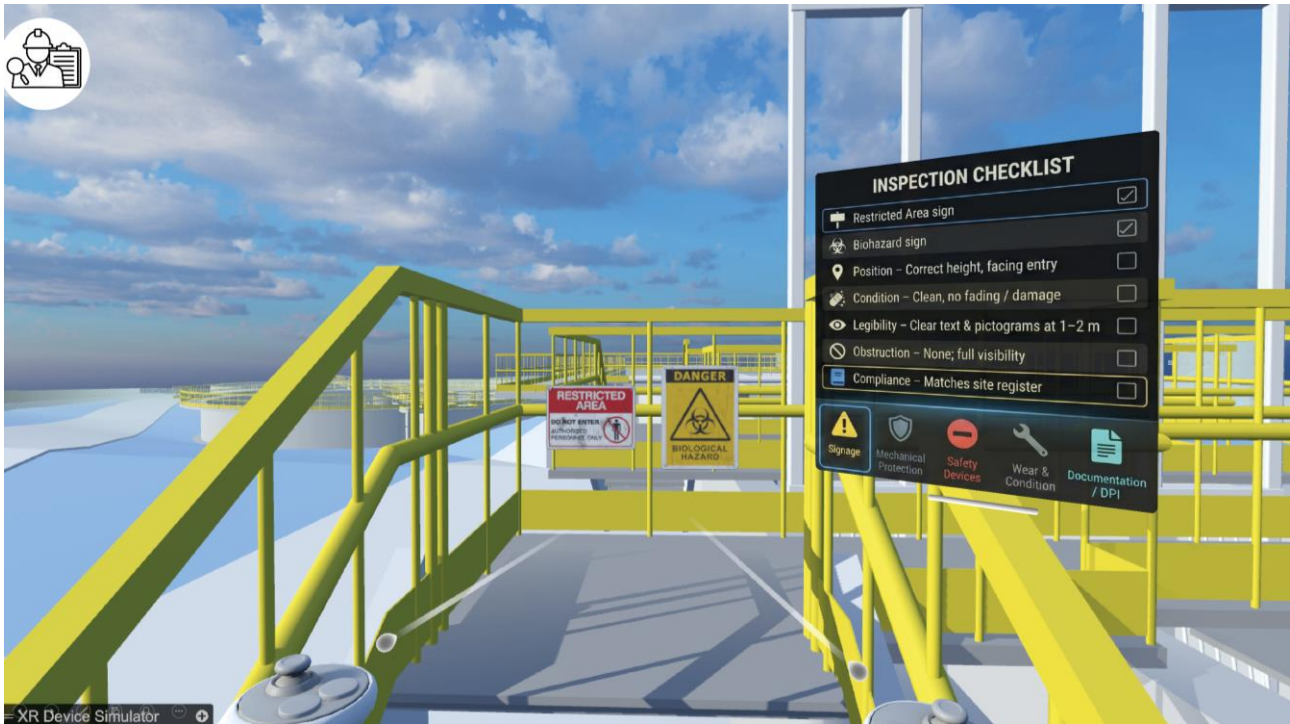


Figure 17: Inspector interactions within the screening unit of the water treatment line

Once the configuration is completed, the user is placed on the corresponding path within the virtual plant. In the operator path, represented in the figure 16, the user appears on walkways and platforms near equipment and local control points. World-anchored panels provide information about mandatory PPE, local hazards, and maintenance requirements, while interactive checklists and task lists support operational activities such as inspections, cleaning, and functional tests. Through these panels, operators can trigger procedural steps, record completion of actions, and, where necessary, query the AI-supported assistant for short, context-aware clarifications based on the technical documentation encoded in the Model Layer.

In the inspector path, shown in figure 17, the same physical locations are augmented with verification tools instead of operational controls. Inspection panels are organised into thematic tabs, such as signage, mechanical protection, safety devices, wear and condition, and documentation/DPI. Each item corresponds to a concrete requirement, for example the presence and correct positioning of safety signs, the integrity of guards, or the accessibility of emergency stops. Inspectors move along the platforms and corridors, observe the scene, and record findings directly in the virtual environment. In this way, inspection practice is turned into a repeatable, measurable interaction sequence aligned with real procedures and regulatory expectations.

Debriefing and KPI measurement

At the end of the path, all profiles converge in a debriefing scene that closes the serious game loop and reconnects the immersive session with the wider customised training platform. In this space, the system aggregates the main elements of the session: selected role and path, visited units, encountered hazard scenarios, completed tasks, and inspection outcomes. For visitors, the emphasis is on which process stages and key messages have been covered; for operators, on the execution of operational steps and responses to abnormal conditions; and for inspectors, on the completeness of inspection coverage and identification of non-conformities.

To make these results evaluable, the system logs relevant user actions as discrete events (for example visited units, activated panels, completed checklist items, and responses to hazard scenarios). These events are

aggregated into profile-specific KPIs such as path coverage and content access for visitors, task and procedure completion for operators, and inspection coverage and non-conformity detection for inspectors. Indicators are presented in the debriefing scene for individual feedback and can be exported or referenced alongside knowledge repositories, classroom activities, and site visits, enabling longitudinal monitoring of training performance and aligning the serious game with the broader training ecosystem. Because the storyline and indicators remain stable across runs, these measures can be compared over multiple sessions for the same user or across different user groups.

7.2.4 Impact

The implementation of the Serious Game shows how immersive technologies can be applied in training for critical infrastructures.

- **Improved safety awareness**, through repeated exposure to realistic but risk-free representations of hazards, signage, and restricted zones.
- **Stronger procedural reliability and decision-making**, as users rehearse task sequences and responses to abnormal conditions with immediate feedback and AI-supported guidance.
- **Increased accessibility to complex operational areas**, allowing staff, students, and visitors to experience units that are normally difficult or impossible to access during normal operation.
- **Evidence-based evaluation of training**, enabled by logging interactions and computing profile-specific KPIs on path coverage, task completion, and inspection performance.
- **Higher engagement and learning effectiveness**, especially for non-expert audiences, thanks to interactive scenes that embed explanations directly in the plant context.
- **Reusability and transfer to other infrastructures**, since the BIM-to-VR pipeline and AI-assisted information layer can be applied to additional facilities within the customised training platform.

Overall, SOTH illustrates how experiential design and immersive technologies can update technical training practices in the water sector, supporting safer, more informed, and more resilient operations.

7.3 Holographic technology

7.3.1 Objectives

Holographic technology represents a paradigm shift in education, offering immersive, interactive, and culturally rich learning experiences.

The objective of this research is to examine how holographic technology can reshape teaching and training by introducing immersive, interactive, and highly engaging learning environments. The goal is to evaluate the potential of holograms to increase users' motivation, enhance understanding of complex subjects, and ultimately strengthen overall learning outcomes. Furthermore, it explores how holographic technology can "augment" lessons by enabling contributions from subject matter experts located anywhere in the world, eliminating the need for physical travel. Indeed, the underlying idea is that through holographic projection, institutions (such as the Civil Protection Agency) can bring global expertise directly into the classroom, promoting collaborative and enriched learning experiences without geographical constraints.

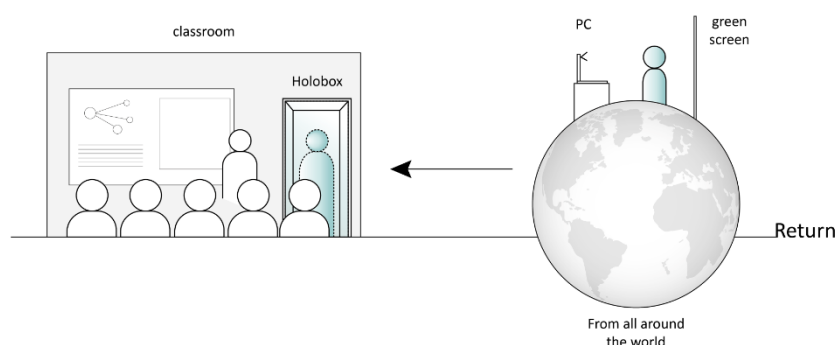


Figure 18: Augment lessons enabled by holographic technology

7.3.2 Methodological approach

The methodological approach adopted is grounded in a comprehensive review of the literature on the evolution of holography and its integration within educational contexts. This review is complemented by an analysis of immersive technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) which serve as synergistic tools to enhance holographic applications in teaching and training.

For more than a hundred years, holography has evolved as a dialogue between light and imagination. Its history is not a mere chronicle of inventions — it is a reservoir of ideas that challenges us to question, reinterpret, and expand the boundaries of reality in our future research.

- **1862:** John Henry Pepper's optical projection introduced 3D illusions.
- **1947:** Dennis Gabor formulated holography theory.
- **1960s–1980s:** Laser advancements enabled practical holograms.
- **2008–2016:** High-profile applications and devices like Microsoft HoloLens brought holography into mainstream technology. This progression underscores holography's interdisciplinary potential and its growing role in education.

This research is anchored by three pivotal questions that frame its scope and objectives, guiding the inquiry toward a deeper understanding of both theoretical foundations and practical implications.

- **(Q1)** What differences could holograms introduce to learning compared to conventional lessons?
- **(Q2)** What challenges do teachers/institutions encounter or anticipate when implementing holographic technologies, and what strategies can be employed to overcome these obstacles?

- **(Q3)** Which strategies and technology are most effective for integrating holographic interventions into traditional lectures, allowing expert to deliver targeted content from any geographical context?

(A1) This section provides an in-depth analysis of how holograms can transform learning experiences compared to traditional classroom methods. Holographic technology introduces several significant pedagogical differences when compared to traditional teaching methods. Conventional lessons typically rely on two-dimensional representations—such as textbooks, slides, and static diagrams—which often limit users' ability to visualize complex structures or dynamic processes. In contrast, holograms provide three-dimensional, spatially accurate representations that can be observed from multiple angles. This immersive visualization capability enhances cognitive processing by reducing abstraction, particularly in disciplines that involve intricate geometries or systems, such as engineering and architecture. Furthermore, holograms foster active learning by allowing users to promote experiential engagement rather than passive reception of information [1]. Research in educational psychology suggests that such interactive environments improve knowledge retention, conceptual understanding, and problem-solving skills [2]. Finally, holograms contribute to motivation and engagement by leveraging novelty and interactivity, which are critical factors in sustaining attention in modern classrooms. While traditional lessons often struggle to address diverse learning styles, holographic environments offer multimodal experiences that cater to visual and collaborative learners simultaneously.

(A2) The challenges that teachers encounter or anticipate when implementing holographic technologies, along with strategies to overcome them, are presented in this section. The integration of holographic technologies into educational environments presents several challenges that must be addressed to ensure effective adoption [3]. Technical complexity is among the most significant barriers; teachers often lack prior experience with advanced visualization systems, which can lead to difficulties in operating hardware and software platforms. This challenge is compounded by the need for specialized infrastructure, including high-performance projection systems and stable network connectivity, which may not be readily available in all institutions. Another critical issue is cost, as holographic equipment and maintenance require substantial financial investment. Limited budgets can hinder large-scale deployment, making affordability a key concern. Additionally, educators may face curricular integration challenges, as existing training plans are typically designed for traditional teaching methods and must be restructured to leverage holographic capabilities effectively.

To overcome these obstacles, several strategies can be implemented. First, comprehensive training programs should be developed to build technical proficiency and confidence in using holographic tools. Second, institutions can adopt phased implementation approaches, starting with pilot projects and shared holographic labs to evaluate feasibility and cost-effectiveness before full-scale adoption. Third, collaboration with technology providers and industry partners can help reduce costs through resource-sharing models and institutional partnerships.

(A3) Holographic projections offer a unique opportunity to allow experts to participate remotely without physical travel, creating global knowledge networks that transcend geographical barriers and promote real-time collaboration [4]. Such integration not only enhances accessibility but also supports inclusive and culturally diverse learning environments. By leveraging holographic telepresence, institutions can cultivate learning ecosystems that are immersive and globally connected.

7.3.3 Use case implementation

The adoption of 3D holographic technology in educational and professional contexts represents a transformative step toward immersive and interactive learning environments. At the university level, holograms enable real-time visualization of complex engineering structures - such as architectural models or infrastructural systems - enhancing spatial comprehension and supporting advanced design analysis.

Similarly, in the domain of public administration, holographic technology offers significant potential for the training of technical personnel responsible for infrastructure management, urban planning, and emergency response. Through holographic simulations, technicians can visualize and interact with complex systems - such as water networks, energy grids, or transportation infrastructures - in a risk-free environment. This approach facilitates scenario-based learning, improves decision-making skills, and supports the development of competencies aligned with smart city and digital twin paradigms.

To ensure effective implementation, **a multi-phase strategy is recommended**. Initial steps include pilot projects and the establishment of shared holographic laboratories accessible to both academic institutions and public agencies. Comprehensive training programs for educators and technical staff are essential to build digital literacy and operational proficiency. Finally, gradual integration into curricula and professional development frameworks - alongside complementary technologies such as Virtual Reality (VR) and Augmented Reality (AR) - will foster blended ecosystems that combine traditional instruction with cutting-edge visualization tools, promoting inclusivity, efficiency, and innovation in both education and public sector training.



Figure 19: Augment lessons with digital model display



Figure 20: Augment lessons with remote lecturer.

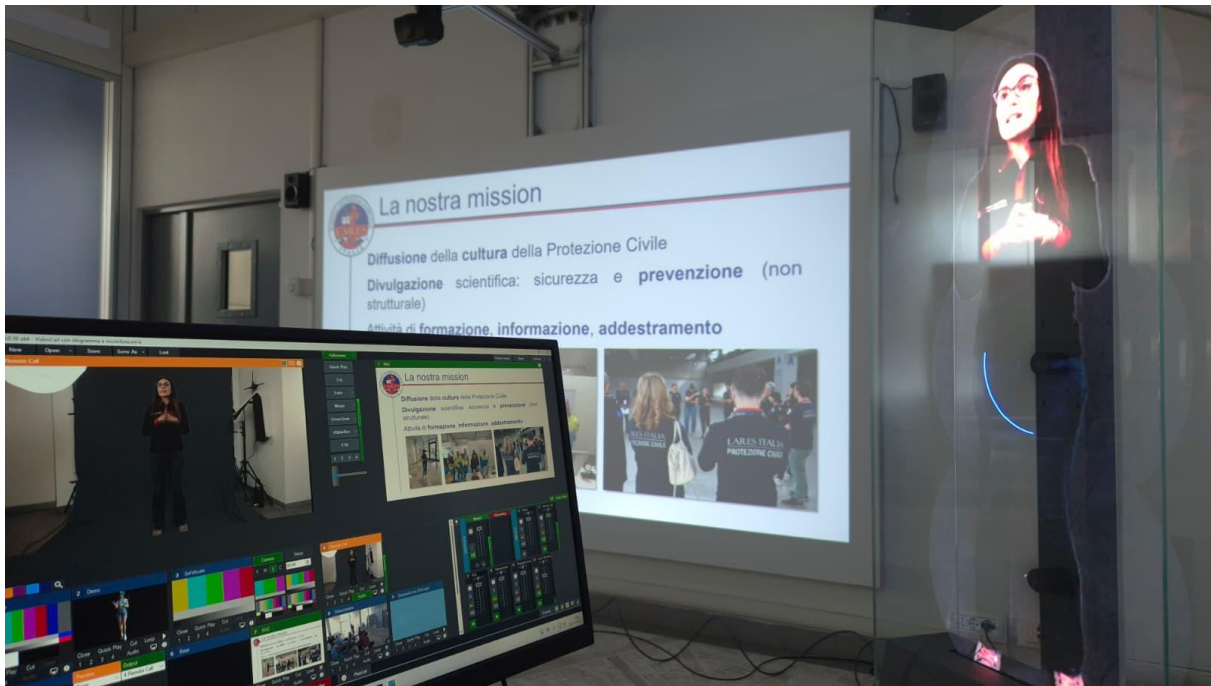


Figure 21: LARES involvement in the Master's Degree course "Conoscenza del Patrimonio costruito nell'epoca dei cambiamenti climatici" at Politecnico di Torino, supporting awareness-raising activities on territorial resilience for students.

7.3.4 Impact

The integration of holographic technology into educational settings offers substantial benefits. Empirical studies on immersive learning environments indicate that such technologies significantly increase users **engagement and motivation**, fostering active participation and sustained attention. Moreover, holographic visualization enhances **comprehension of abstract or complex concepts** by providing three-dimensional representations that support cognitive processing and spatial reasoning. These features also accommodate diverse learning styles, enabling multimodal interaction and promoting collaborative learning experiences.

From an institutional perspective, the adoption of holographic solutions positions educational organizations as innovators in 21st-century pedagogy, reinforcing their commitment to technological advancement and **global connectivity**. Immersive experiences facilitated by holograms encourage cultural awareness and inclusivity, creating opportunities for **cross-border collaboration** and exposure to international expertise without the constraints of physical mobility.

Looking ahead, the future trajectory of holographic education is closely linked to **emerging technologies** such as artificial intelligence and digital twins. AI-driven holographic tutors could provide personalized learning pathways, adaptive feedback, and real-time analytics, while integration with metaverse platforms may enable fully immersive, persistent learning environments. To validate these innovations, future longitudinal studies on knowledge retention, performance outcomes, and cognitive load will be essential, ensuring that the pedagogical effectiveness of holographic interventions is supported by robust empirical evidence.

8. Cross-Competence Development

8.1 Design Thinking for Asset Management Training

8.1.1 Objectives

In the context of PhD education, where the focus is on advancing knowledge and developing original solutions, integrating the Design Thinking can be instrumental in stimulating researchers' creativity and fostering the emergence of new ideas. This section describes a creative design experience aimed at developing effective innovative solutions for asset management workforce training, conducted in the third-level hard skills course "Digital Twin, Virtual Reality and Metaverse: technologies to support the asset management workforce" in within the Doctoral College of Civil and Environmental Engineering at Politecnico di Torino. The activity involved the participation of 10 Politecnico di Torino PhD students characterised by different levels of progression concerning their research path, i.e. attending cycles 38 to 40 and coming from different PhD programmes. The course attracted students' interest from the PhD programmes in Civil and Environmental Engineering, Electrical, Electronics, and Communications Engineering and Urban and Regional Development, as it addressed the topic of critical infrastructure management. The diverse backgrounds of the participants in engineering and architecture are valued as a strength for the activities, as they enable a broader and more stimulating multidisciplinary interaction, bringing in different skills, viewpoints, and experiences.



Figure 22: Third-level course experience

8.1.2 Methodological approach

The course was structured around the Design Thinking framework, alternating divergent and convergent thinking phases to explore both the problem space and the solution space. This framework allowed participants to identify, analyse, and address the complex challenges of asset management workforce training through iterative, human-centred and evidence-driven processes.

Step 1 – Introduction and Context Setting

The first session clarified objectives, introduced the participants and their research fields, and established the foundations for collaborative co-design activities. Recognising each participant's background was crucial to create the shared knowledge base required by Design Thinking methodologies, where each contributor becomes an active designer and co-creator.

Step 2 – Problem Definition

The initial focus is on the problem space empathy and definition. What was the initial situation? What was the problem with that situation? What problem do you want to solve? Why does this problem exist at all? What kind of problem is it? What are its different characteristics? What makes it a difficult problem to solve? What are the context conditions? Who were the stakeholders? What might have been done differently? These are just some of the questions that can guide us in examining the problem in depth, continuing to re-state, re-frame and redefine it according to different aspects in concrete and tangible terms. Problems formulated in a generic or abstract way hinder an understanding of the true nature of the negative aspect to be faced and, therefore, make it difficult or impossible to define the appropriate way to deal with it.

Through guided reflection, participants defined the training challenges in asset management using:

- Problem tree diagram: that helps to relate problems in a hierarchical order from bottom to top according to an analytical approach that makes explicit cause-effect relationships once the main one to start from has been defined. While this overview deconstructs and expands the problem, it also helps to better focus attention on a confined portion of the issues that can really be addressed through project objectives but with a broader overview that can determine their success. This step is crucial, although often overlooked or neglected, as it stimulates reflection on the relevance of research, directing it towards solutions that respond to actual, rather than abstract, threats. In the context of the challenge examined, for example, it emerged that issues related to asset management workforce training are of a varied nature and complexity. Although engineers were inclined to examine the pragmatic, technical, and technological aspects initially, it was immediately evident that there were multiple dimensions to be considered to determine the success of a possible project proposal. Training, in fact, should carefully consider the target audience it is aimed at, its characteristics, and the social, cultural and corporate context of reference. Therefore, the solution's user experience and feasibility are highly conditioned by aspects not directly linked to its technological quality.
- Stakeholder map technique: to force a visual representation and a clear understanding of all the actors involved or interested in a project, initiative or decision-making process. At this stage, researchers are asked to spend time carefully examining the problem, considering the different needs and viewpoints of the actors. Actors were clustered according to criteria such as their level of influence and interest in the problem. Asset management workforce training is a complex issue involving many stakeholders.
- SWOT analysis and system map techniques: to understand the interactions, dynamics, and interconnections between the different components of a complex system. Once the initial reasoning is summarised using the problem tree approach, the students are called upon to transform the diagram created by moving from each specific problem to a linked possible action.

All the mentioned activities are conducted by providing time for individual reflection, collective discussion and final individual reflection to stimulate participation and expression of everyone's opinion. This phase encouraged participants to recognise not only the technical, but also the social, organisational, and cultural dimensions of training design.

Step 3 – Observation and Technological Exploration

Students explored the potential of the most promising technologies that can be used in training activities, such as Augmented, Virtual, and Mixed Reality tools and Metaverse applications for workforce training. Through hands-on trials, participants experienced immersive systems and analysed state-of-the-art examples, discovering how technologies such as Digital Twins and AI can support experiential learning and simulation. Although this activity was time-consuming in organisational terms, it made it possible to overcome possible knowledge misalignments among the participants also due to their different backgrounds and knowledge. At the same time, participants are also encouraged to investigate the state-of-the-art applications of these technological solutions in related contexts or through replicable approaches. Each student approached the research according to their research interest and perspective. Consequently, the outputs were wide and varied providing further input to broaden or better define the Tree problem diagram. Studies dealing with literature reviews on the use of specific technologies and experiences developing virtual reality applications for activities in industrial and infrastructure contexts were reported. Other students focused, on the other hand, on the in-depth investigation of social and psychological aspects, finding reflections on the culture and age of workers and how technologies are introduced. Finally, the Operator 5.0 paradigm emerged as a new challenge, seeking greater resilience in systems based on the combination of user resilience and key enabling technologies. Sharing the experiences encountered energizes the following initial brainstorming on possible actions to be taken to achieve the objectives and enriches the individual's learning.

Step 4 – Ideation

Students are invited to brainstorm on the formulation of training solutions according to a divergent approach.

- **Analogy mapping:** to identify problems and solutions in one domain and apply them to another. This concept works by recognising relational similarities between things in different domains. For example, organisations need to invest in training to enable staff to develop and adapt like a gardener caring for plants to grow. Staff skills may wither or fail to adapt to change if attention is not paid (such as neglecting watering or pruning). Students were then asked to reflect on the opportunities derived from the analogies concerning asset management workforce training. The possible analogies were individually evaluated, shared and explained with the group and then collectively revised. Just as video games are a source of entertainment, technologies can help engage the user in educational and training contexts through a game approach. Alternatively, just as an orchestra must act in a synchronised manner in order to return a harmonious melody, workers must have a strong commitment from above in order to act cohesively. Starting from the three analogies rated most promising, the students concentrated on generating solutions exploiting strategies derived from other contexts. When some preliminary ideas begin to emerge, it is helpful to introduce techniques that stimulate the ideas through a series of questions and expand how they can be manipulated or developed.
- **SCAMPER list** has been illustrated as offering an organised, systematic and practical way to stimulate the imagination and is based on the idea that everything new comes from a modification of something that already exists. Each letter that makes up the acronym represents a word related to a question that must be asked to support the development of an idea or graft new solutions by playing with its characteristics. S means substitute and intends to replace one thing for another (e.g. parts, people, processes, materials, rules). C, combining one thing with another. A, adapt, doing something else (e.g. another purpose, role, function). M, modify something (e.g. the arrangement, the parts, the whole, the interactions, the cause, the effect). P, put to other use, use things for another purpose (e.g. the parts, the whole, the input, the output, use these in other applications, sectors). E, Eliminate something (e.g. parts, people, processes, materials, rules) R, reverse things. Within the ideation context, it is possible to assess the effectiveness of the creative process through four measures that take into account fluidity, i.e. the quantity of ideas produced, their flexibility in terms of variety and diversity, originality and their level of elaboration. The multitude of ideas that emerge must then be grouped, combined and reduced to begin formulating real solutions to the problem that can be designed in more detail.

Step 5 – Prototype

The teams proceeded to prototype their ideas, translating abstract concepts into tangible forms in order to collect feedback, validate assumptions, and refine their proposals. Among the different approaches introduced during the course, role-play prototyping was selected as the most effective method for this context. It is an active simulation technique that allows participants to quickly elicit the user experience of a product or service by enacting real-world interactions and observing behavioural responses. The collective scenario focused on designing a Virtual Reality learning platform based on interactive Digital Twin models of a hydropower infrastructure. The case study included training tasks for management and maintenance personnel, as well as an outreach component designed for community awareness and dissemination. To test the concept, the participants conducted a role-play simulation replicating a multi-stakeholder roundtable to evaluate the feasibility of the proposed training solution. Each PhD student impersonated one of the key stakeholders potentially affected by the project, including an IT developer, software designer, infrastructure engineer, operations manager, maintenance technician, HR representative, trade-union delegate, safety officer, and public-administration official. The diversity of roles, reflecting both public and private, internal and external perspectives, mirrored the Stakeholder Map developed in the earlier phase and ensured a wide range of viewpoints during the discussion. The instructor also participated, acting as the infrastructure concessionaire, guiding the debate and ensuring balanced consideration of all arguments. Following an initial presentation of the concept by the IT developer, the session evolved into a structured dialogue where multiple stakeholder perspectives converged. This exchange made it possible to identify divergent needs, conflicting priorities, and critical dependencies, while collaboratively analysing the strengths and weaknesses of the proposal. Feedback gathered in this phase informed a collective effort to refine and improve the prototype. The role-play exercise proved particularly effective for evaluating complex educational solutions, highlighting that focusing exclusively on technical performance can lead to shortcomings if economic, social, or cultural dimensions are neglected. As emerged from the earlier Problem Tree analysis, factors such as worker motivation, recognition of innovation-oriented behaviours, and the integration of training into professional certification processes are equally crucial for success. Overall, the collaborative and experiential setting fostered an atmosphere of creative and critical thinking, enabling participants to conceptualise training solutions that were both innovative and pragmatically grounded in real-world operational contexts.

Step 6 – Testing

Testing is the final stage of the design thinking process, where prototypes are presented to public users for feedback. In the course context, this phase corresponds to the experimentation that the individual participant is encouraged to do within their research field by exploiting the learned method. This prompt motivates them to continually refine their work to effectively respond to identified needs through a more structured and measurable approach.

Results

To collect feedback on the teaching approach adopted in the course, a questionnaire was administered to participants at the end of the final session. The results show a high level of appreciation for the structure and delivery of the activities, which fostered strong engagement and encouraged students to take an active role throughout the learning process. The use of Design Thinking was considered effective for addressing complex research problems, and students reported that they intend to adopt the methodology as part of their toolkit for future research challenges. Early-stage PhD students, in particular, highlighted its value in supporting exploration, problem-framing and the identification of alternative solution pathways. Among the techniques tested, 40% of participants identified the Problem Tree analysis as the most effective tool, while the remaining votes were distributed across the other methods. This finding confirms the need for a greater emphasis on problem definition in research processes and highlights the importance of avoiding premature convergence on solutions. At the same time, the absence of a dominant preference for the other techniques indicates that all contributed meaningfully to structuring and supporting the creative process. Regarding the specific challenge addressed, students recognised the strong potential of emerging technologies in training for the asset management workforce. Interactivity, customisation, game-based dynamics and collaborative features emerged as the most promising aspects for real-world implementation. The size of the group (10 students) was considered optimal, ensuring productive interaction with the instructor and among participants, and enabling the achievement of the planned objectives. However, it was

also noted that greater diversification of disciplinary backgrounds could enhance the divergent phases of the process - improving fluency, flexibility and originality of ideas - and support more sophisticated convergence towards robust and innovative solutions. In line with the analogy-mapping technique explored during the course, students highlighted how identifying relational similarities across domains can foster originality and promote connections between seemingly distant problems, enriching the ideation process. A further enhancement to the learning experience derived from the adoption of role-play prototyping, a method rarely used in conventional academic settings. By integrating visual, auditory and kinaesthetic dimensions, role-play simulations enabled participants to reproduce realistic professional scenarios and acquire practical competences. This experiential approach supported a deeper understanding of human dynamics, organisational behaviours and multi-stakeholder interactions. Moreover, it strengthened key transversal skills, including teamwork, communication, conflict management and leadership, within a safe environment that mirrors and anticipates real operational contexts.

8.1.3 Impact

The innovative learning framework exemplifies the transformative potential of combining Design Thinking with emerging digital technologies to advance asset management workforce training. The course experimentation not only aligns with current research trends but also reinforces the technology-transfer mission at the core of RETURN, bridging Education, Research and real-world operational needs. By integrating leading technologies a structured design methodology, the course demonstrates how technological innovation can be effectively transferred into training practices, enhancing the preparedness, awareness and adaptability of the future asset management workforce. The adoption of a Design Thinking approach promotes an educational model capable of enhancing creativity, divergent thinking, teamwork and empathy, while cultivating essential social and communication competencies, problem-framing, negotiation, active listening and the ability to integrate multiple perspectives into shared objectives. In this respect, the course operates as a technology-transfer laboratory, where doctoral students learn to convert technological opportunities into applicable, user-centred training solutions for complex socio-technical systems. Embedding Design Thinking in doctoral programmes thus serves as a catalyst for strengthening researchers' capability to respond to societal challenges through iterative, inclusive and human-centred innovation processes. The methodological framework experienced in the course has proven valid, replicable and scalable across educational, academic and professional contexts. Its adaptability makes it particularly well-suited for transfer to the RETURN project, where broader participation of stakeholders in the risk management and critical infrastructure fields will support the expansion of the Problem Tree analysis and the co-development of research prototypes with strategic impact for the asset management workforce.

A further consolidation of this technology-transfer trajectory occurred through the replication of the experience in an international Erasmus+ mobility context at a leading European technical university. The methodology was implemented with a new audience of researchers and practitioners, confirming its transferability across institutional and cultural environments. This international application also served as a European dissemination action for RETURN, showcasing how methodological innovation combined with advanced digital technologies can effectively support workforce development in the field of critical infrastructure asset management.

Overall, the experience confirms that embedding Design Thinking into advanced training pathways enhances research creativity, accelerates technology transfer, and increases societal impact—strengthening the integration between education, technological innovation and resilience within both the RETURN ecosystem and the wider European research landscape.

8.2 Knowledge Hub Platform

8.2.1 Objectives

The Knowledge Hub Platform serves as a comprehensive ecosystem supporting continuous skills development and knowledge management within complex organizational and institutional settings. It aims to foster upskilling and reskilling through personalized, adaptive learning paths aligned with evolving professional profiles and operational needs. The platform enhances organizational culture by encouraging collaboration, knowledge sharing, and multi-stakeholder engagement across different roles, disciplines, and geographic areas.

8.2.2 Methodological approach

The Knowledge Hub supports continuous skills development through a modular and scalable platform architecture that integrates tools for upskilling and reskilling. The training ecosystem is modular and provides access to structured courses, multimedia resources, and collaborative learning methods. It stays consistently aligned with the needs of different professional profiles.

The training section includes courses, webinars, interactive workshops, and e-learning modules organized by progressive levels of depth. Each item contains clear descriptions, multi-format materials, and assessment tests that support gradual learning. Users can obtain digital badges and recognized certifications. The catalog is continuously updated and combines internally developed content with resources from certified external providers, ensuring relevance to current regulations and emerging innovations.

To support the training process, the platform provides technical tutorials, operational guides, and microlearning content that promote the rapid acquisition of specific skills. Searching materials are facilitated by an indexing system that quickly identifies the content most relevant to the user's needs. The experience is further enhanced by a recommendation engine that suggests personalized courses based on the user's profile, previous experience, and identified training needs.

The environment includes collaborative spaces where users, experts, and institutional stakeholders can engage in thematic forums, communities of practice, multidisciplinary working groups, and participatory review activities. Multichannel messaging and notification systems facilitate the sharing of experiences and strengthen the organizational culture based on cooperation and professional growth.

A central element of the platform is Ragnarok, the intelligent system, integrated into the platform, that personalizes training paths and ensures continuous content updates.

The system provides an integrated, real-time updated course catalog covering both transversal skills and specialized technical expertise. Content may be internally developed or provided by certified external providers. The courses offer various levels of depth, personalized assessments, and digital badges for certifying acquired skills. This supports the enhancement of professional profiles and facilitates internal mobility across roles and functions.

Finally, integration with technical documentation and the institutional knowledge base allows users to contextualize training in real-world scenarios, connecting learning to the operational needs of the local area and the adoption of innovative methodologies, with a view to continuous improvement and responsible knowledge sharing.

Training Catalog

The central element of the training offering is the Training Catalog, a dynamic system with courses, webinars, interactive workshops, and e-learning modules organized by subject area, level, and user profile. Each content includes descriptive sheets, multi-format learning paths (videos, technical documents, tests), automatic assessments, and digital badges for certification. It also features an intelligent recommendation engine that suggests the most suitable learning paths based on existing skills and identified learning gaps. Content is continuously updated and integrated with certified external providers, keeping training aligned with new regulations and emerging technologies. Progress tracking dashboards provide visibility into results achieved and certifications acquired.

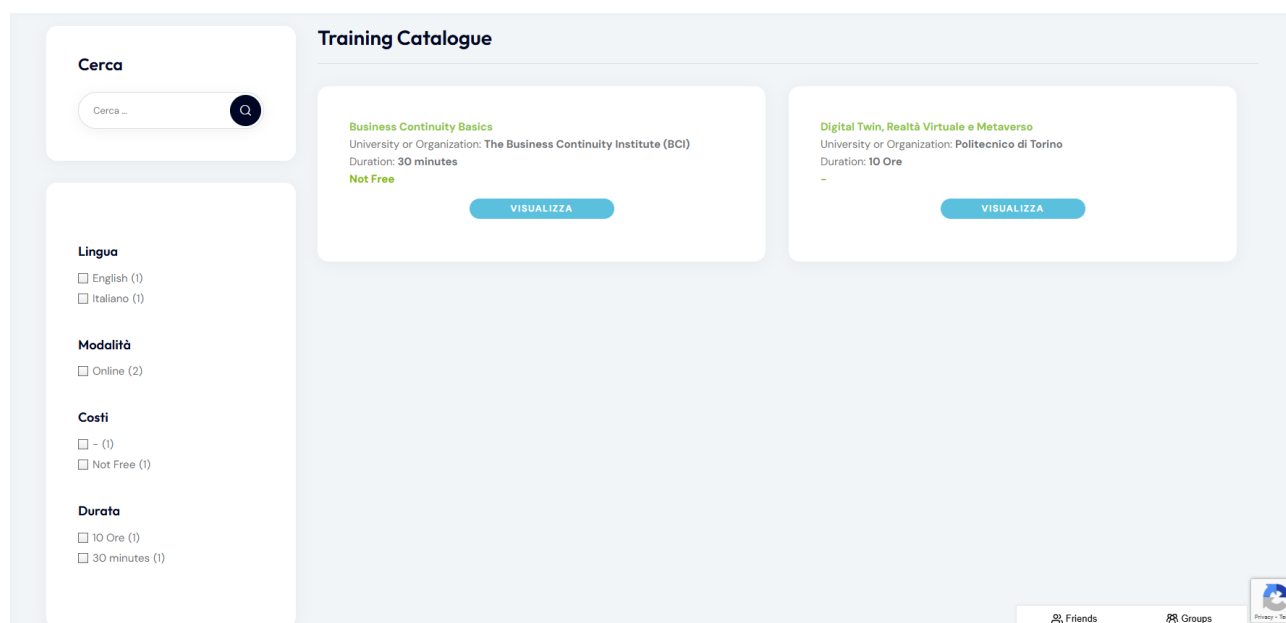


Figure 23: Training Catalog

Solutions and Knowledge Resources

The Solutions and Knowledge Resources section represents the platform's structured documentation hub. It includes technical and procedural documentation (manuals, SOPs, guidelines), interactive glossaries that ensure terminological consistency, and publications such as articles, case studies, and lessons learned. Documentation is semantically indexed, versioned, and open to contributions, comments, and revisions, enabling continuous improvement.

The platform fosters collaboration through thematic forums, communities of practice, multidisciplinary working groups, peer review spaces, and virtual mentorships. These are integrated with multichannel messaging and notification systems that facilitate the exchange of experiences between experts, junior staff, and institutional stakeholders, contributing to the strengthening of organizational culture and internal collaboration.

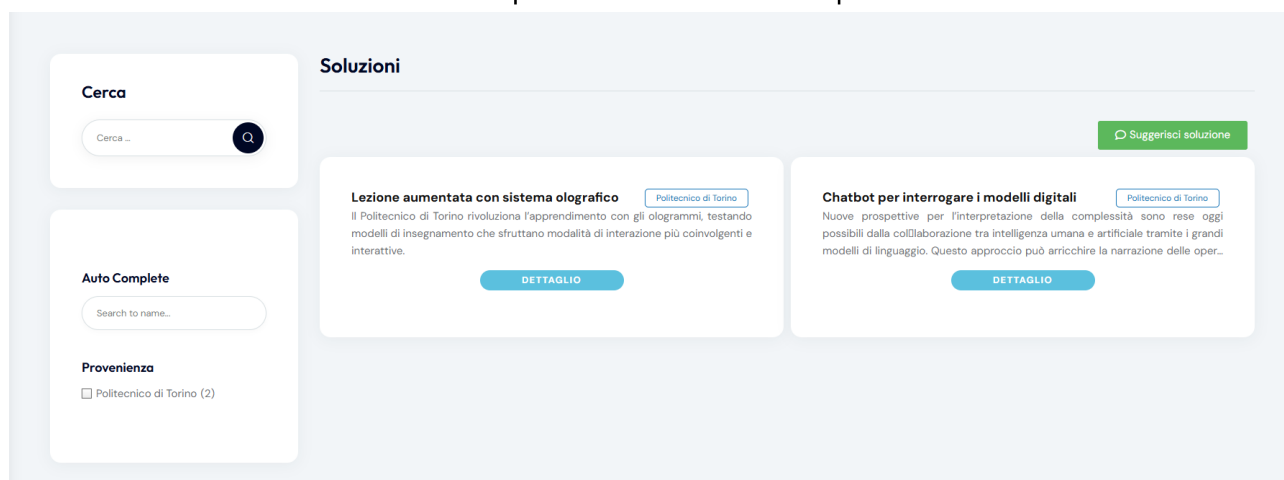


Figure 24: Solutions

Education Technology Glossary

The Education Technology Glossary section is a key element supporting the "Solutions" and "Training Catalog" areas. The RETURN Glossary (see Annex 2) provides a structured collection of technical terms, key concepts, and Project-specific definitions, offering users - professionals, operators, and citizens - an authoritative and easily accessible reference point. This tool allows for quick access to clear, contextualized explanations, avoiding interpretative ambiguities and ensuring consistent use of industry terminology.

The glossary therefore plays a cross-functional role, promoting consistency of concepts among users with different levels of experience, simplifying the understanding of training content and technical documentation, and providing immediate support during course use and resource consultation. Fully integrated with the Training Catalog and the Solutions section, it helps consolidate the Knowledge Hub as a comprehensive ecosystem, focused not only on training and documentation but also on ongoing support for navigating and assimilating professional and operational content. The Glossary is therefore an indispensable tool for ensuring clear, effective, and shared communication within the platform.

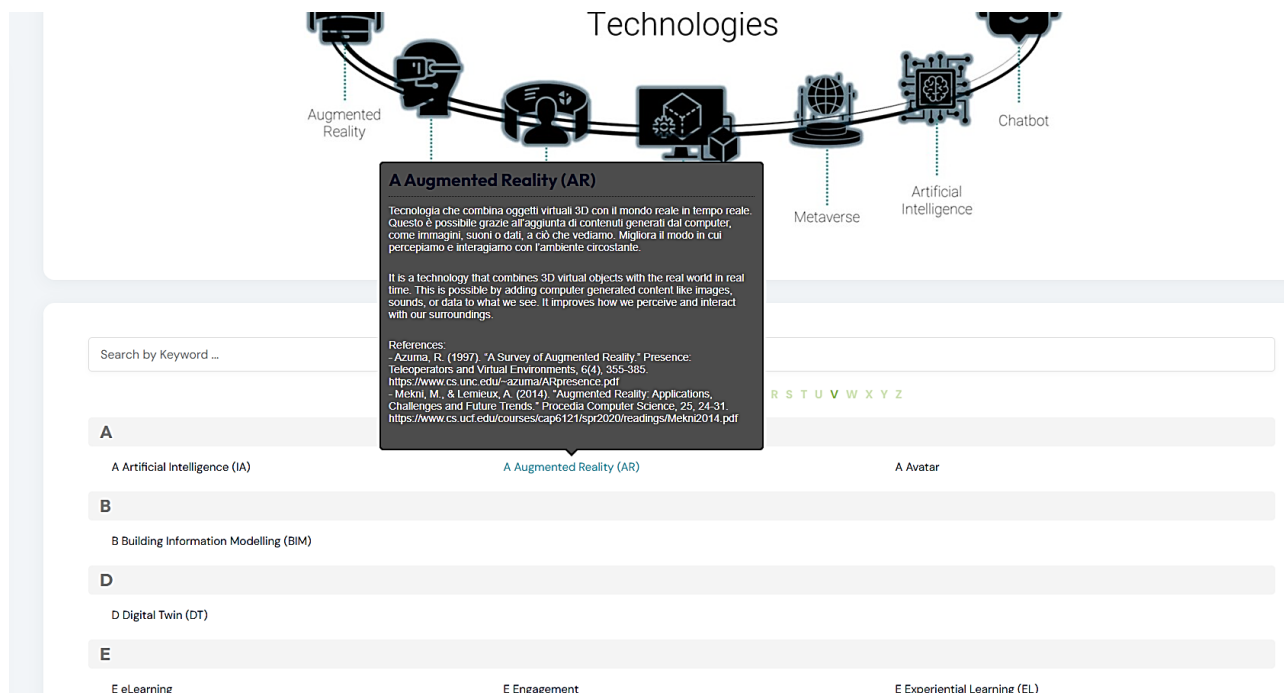


Figure 25: Education Technology Glossary

Overall, the glossary improves the quality of learning and interactions, promoting responsible knowledge management within the Knowledge Hub's institutional and professional community.

Smart Box

The Smart Box, as part of the platform's architecture, is a strategic tool supporting the expansion of knowledge and development of competencies. It enhances upskilling and reskilling processes through real-world, hands-on learning experiences and validation. By moving beyond a purely digital approach, the Smart Box acts as a territorial laboratory, allowing users to directly test the platform's features, acquire new skills, and validate their knowledge in environments marked by the complex interdependencies of critical infrastructure and natural phenomena.

The Catalogue component provides a centralized inventory of field data, analytical outputs, and supporting documentation, giving users access to practical training materials and up-to-date professional resources. The Explorer interface enables advanced geospatial data exploration, visualization, and scenario comparison, strengthening the ability to analyze territorial dynamics and system interactions.

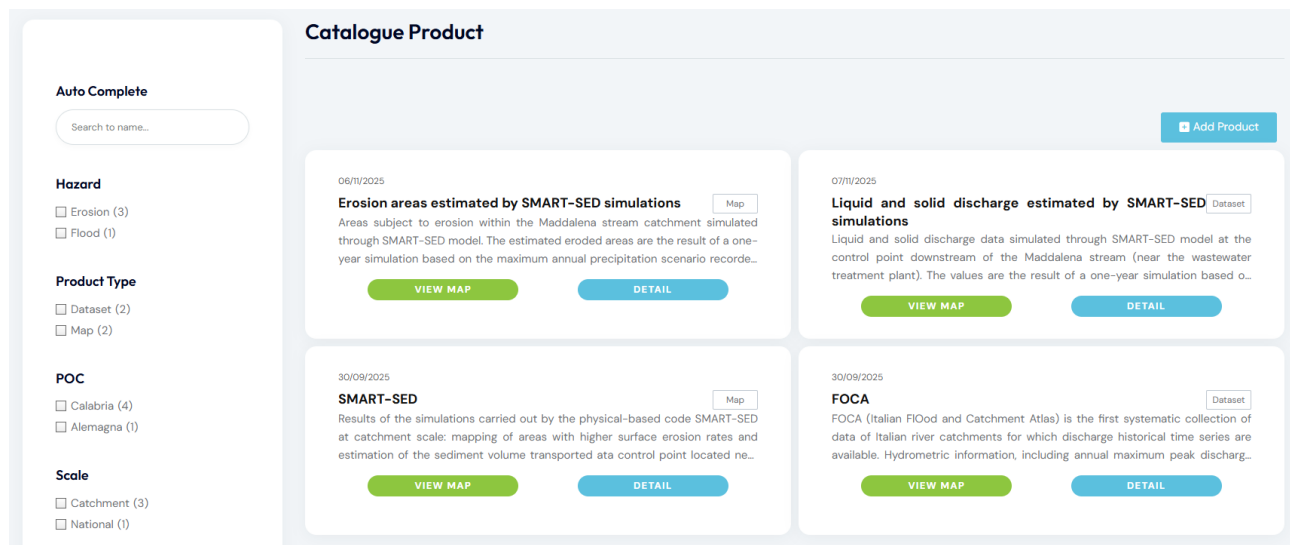
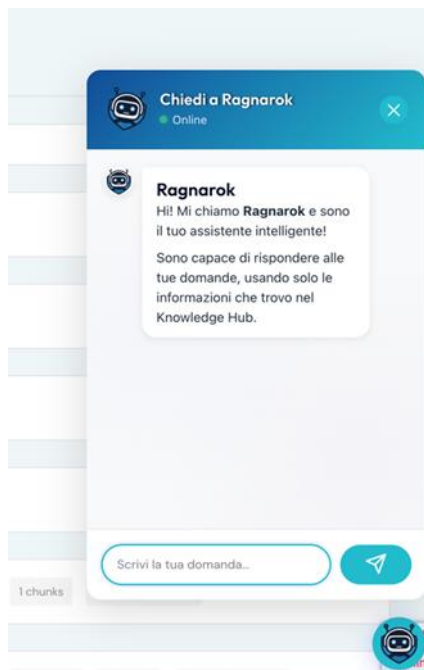


Figure 26: Catalogue Product of the Smart Box section

This architecture transforms the Smart Box into an active knowledge and skill development module—an “on the job” learning platform. It lets operators, technicians, and stakeholders gain hands-on expertise via mission-based monitoring, simulations, and real-world testing, enhancing analytical, technical, and problem-solving skills critical for managing strategic infrastructure. The distributed network of Smart Boxes across complex territories constantly feeds the institutional knowledge base with empirically validated data and case studies, creating ongoing opportunities for situational learning.

In summary, the Smart Box serves as an advanced support for organizational upskilling and reskilling, turning validated field information into immediately applicable skills and fostering a learning organization and increased resilience in high-impact operational contexts.

Ragnarok Technology



An innovative and distinctive feature of the platform is the integration of Ragnarok, an AI-driven system designed to optimize training processes and customize them based on user needs. Ragnarok enables the automatic generation of learning content, quizzes, and adaptive courses, supporting just-in-time learning and the use of content in microlearning mode. It also provides digital assistants capable of answering technical questions, guiding users through documentation, and providing personalized and ongoing support.

The system also facilitates the automatic updating of documentation, glossaries, and training materials, connecting internal and external sources to keep the knowledge base constantly aligned with regulations, standards, and emerging innovations. By analyzing user interactions, Ragnarok contributes to the review process with targeted suggestions and optimizes the recommendation engine by identifying content, courses, and thematic workgroups based on skills, interests, and platform usage behavior.

The integration of Ragnarok makes the Knowledge Hub an advanced learning environment, capable of offering highly personalized and proactive experiences, accelerating professional development processes and improving the resilience and competitiveness of the entire organization. Finally, the platform facilitates content management and sharing: experts can upload multimedia materials and documentation, while operators and citizens can access it to acquire knowledge, guided, when necessary, by AI suggestions that direct them to the training paths most relevant to their needs.

Ragnarok Documents Manager

636
TOTAL DOCUMENTS

569
PROCESSED

2567
TOTAL CHUNKS

2567
INDEXED CHUNKS

Documents List

ID	Title	Type	Chunks	Indexed	Status	Date	Actions
1648	Ragnarok	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1646	Analytics Survey	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1647	CI	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1645	Survey Test	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete
1644	Critical Infrastructure Protection in the Water Sector: A 2030 Outlook	html	1	1 / 1	Completed	2025-11-03 14:43	Reprocess Generate Embeddings Delete

Figure 27: Ragnarok Documents Manager

Thanks to this intelligent and integrated architecture, the Knowledge Hub is a strategic tool for innovation in training and knowledge management. Its modularity and scalability make it suitable for diverse institutional and production contexts. It supports continuous skills growth and encourages responsible dissemination of knowledge within a complex community.

8.2.3 Impact

By combining digital resources, real-world experimentation, AI personalization, and collaborative knowledge exchange, the Knowledge Hub fosters professional development, internal mobility, and organizational resilience. It transforms training into an interactive, continuously evolving process that integrates formal education with practical application, enabling users to rapidly acquire and validate skills critical for managing complex systems and infrastructures. The platform also strengthens organizational cohesion by embedding a culture of cooperation, responsible knowledge sharing, and innovation-driven growth across institutional and production contexts.

In summary, reformulating the report by focusing on these elements aligns it with the platform's strategic purpose, methodological rigor, and transformative impact on professional competence and knowledge ecosystems. This approach underscores the Knowledge Hub as a cutting-edge tool for innovation in continuous learning and knowledge management.

9. The Resilient Operator concept

Digital transformation, increased systemic risks and the growing complexity of critical infrastructure require a redefinition of the role of professionals engaged in asset management. In this context, the figure of the Resilient Operator emerges: a worker who is not only capable of managing assets and processes, but also of adapting, learning, and reacting effectively to new challenges and work ecosystems. This concept resonates strongly with recent discussions on Construction 5.0 and Operator 5.0, where the evolution of industrial paradigms emphasizes human - centricity, sustainability, and resilience. The Resilient Operator can thus be interpreted as the critical infrastructure counterpart of Operator 5.0, embodying the fusion between human expertise and machine efficiency. In this vision, operators are no longer passive executors but active co - creators of resilient systems, able to collaborate with advanced technologies - digital twins, AI, IoT, and automation - while preserving the centrality of human judgment and adaptability. Recent literature also highlights that the COVID - 19 pandemic exposed the fragility of existing manufacturing and infrastructure systems, underscoring the workforce as both the most agile and most vulnerable resource. Making human operators more resilient - through training, education, and systemic support - becomes the cornerstone of building organizations capable of withstanding disruptions. The Resilient Operator 5.0 paradigm, developed in the context of Industry 5.0, demonstrates how resilience must be framed not only at the technological or systemic level, but also at the human one, strengthening cognitive, emotional, and collaborative dimensions alongside technical expertise. Within the critical infrastructure domain, the Resilient Operator thus emerges as a new professional paradigm, bridging tradition and innovation, and combining established technical skills with the flexibility, agility, and cross - domain awareness required by today's contexts. Their training and development represent the most advanced outcome of reskilling and upskilling programmes supported by Education Technology.

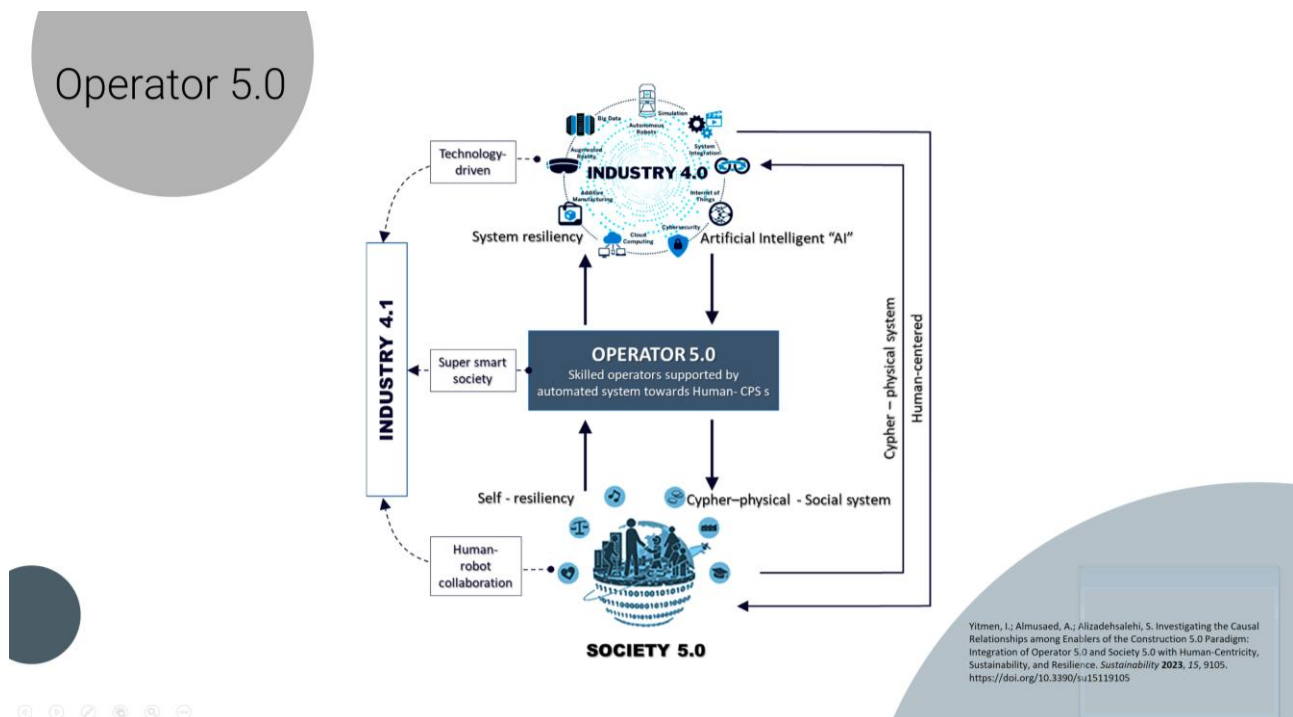


Figure 28: Operator 5.0 paradigm

Resilient Operator

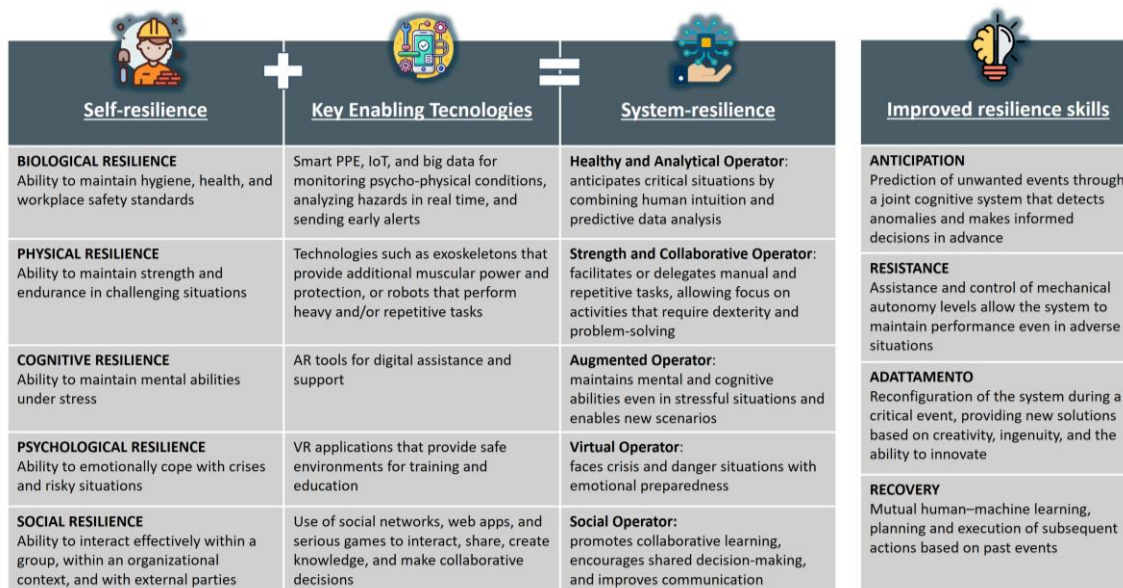


Figure 29: Operator 5.0 skills

10. Conclusions

This deliverable has presented a coordinated set of technological and methodological solutions aimed at advancing the re-skilling and up-skilling of the critical infrastructure workforce. The development of multiple innovative tools demonstrates how advanced Educational Technologies can elevate experiential learning, strengthen procedural reliability, and improve operational situational awareness. The Knowledge Hub Platform consolidates these efforts by offering an integrated, scalable environment that supports continuous learning, structured knowledge exchange, and AI-enabled training guidance. Collectively, the activities conducted define a coherent and forward-looking framework for modernising workforce development in the critical infrastructure domain, enabling the emergence of competent, adaptive, and resilient professionals capable of operating effectively within increasingly complex socio-technical systems.

11. Annexes

- **Annex A:** Rethinking Education on Critical Infrastructure Resilience and risk management: Insights from a Systematic Review
- **Annex B:** Knowledge Hub Glossary of Technologies

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Annex 1

Abstract

The growing complexity and interdependence of critical infrastructures, increasingly exposed to natural and technological hazards, call for innovative educational approaches to enhance resilience and risk management. This study examines global trends, research patterns, and challenges in integrating digital and immersive technologies into education and training for professionals and communities engaged in critical infrastructures management. A systematic review of peer - reviewed literature was conducted, analyzing a corpus of studies across six dimensions: technological approach, pedagogical model, hazard typology, infrastructure domain, stakeholder category, and implementation phase. The analysis reveals a growing shift from traditional 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 the widespread adoption of these innovations. The findings underscore that digital and immersive technologies are pivotal to reconfiguring education and training frameworks, enabling the formation of Resilient Operators endowed with adaptive cognition, continuous learning capacities, and effective 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 (CIs) 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, 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].

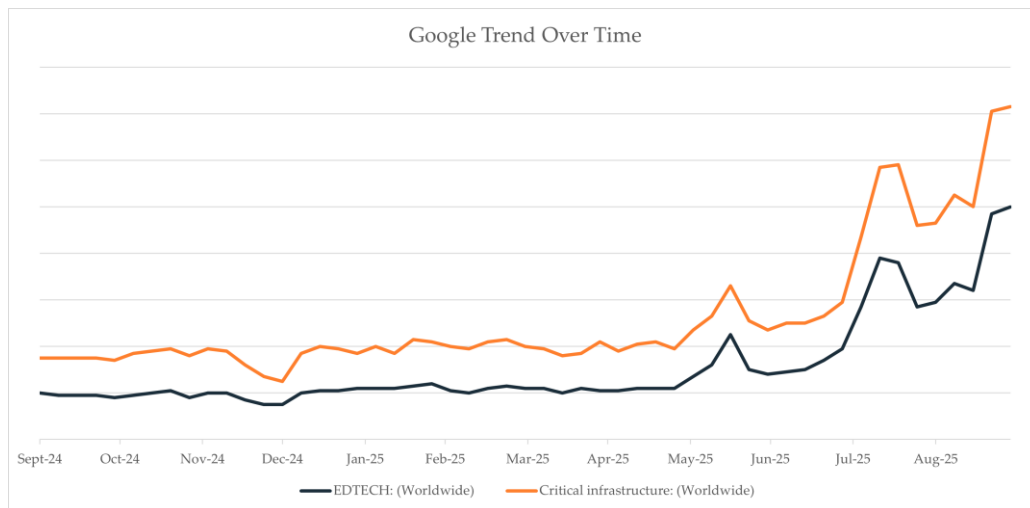


Figure 1: Evolution of global search interest in “EdTech” and “Critical Infrastructure” over time.

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.

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.

Specifically, this review investigates how academic research and applied initiatives address four interrelated dimensions:

- the integration of Educational Technologies into professional training;
- the evolution of pedagogical models in technical and engineering education;
- the role of stakeholders and institutions in promoting adaptive learning ecosystems;
- the development of competencies that underpin resilience and systemic awareness.

By critically analyzing studies across different technological, disciplinary, and geographical contexts, the review seeks to provide insights for rethinking education on critical infrastructure, guiding future research and policy development.

The following sections detail the methodological approach adopted (Section 2) and the paper analyzed (Section 3), explore the educational and technological challenges (Sections 4), and discuss emerging trends and future directions (Sections 5).

2. METHODOLOGICAL APPROACH TO RESEARCH

This literature review adopts a systematic and interpretative approach to explore how education, training, and capacity building are evolving in the field of Critical Infrastructure management. The goal is to identify trends, challenges, and opportunities emerging from the intersection of digital transformation, resilience - oriented governance, and educational innovation.

Following the guidelines for systematic reviews in multidisciplinary research, the process combined quantitative and qualitative methods:

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

The review procedure consisted of five main phases: (i) definition of research questions; (ii) search and retrieval of publications; (iii) screening and eligibility assessment; (iv) data extraction and classification; and (v) interpretative synthesis and validation.

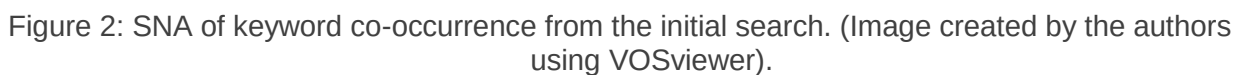
2.1. Research Approach

Given the multidisciplinary nature of the topic, the review follows a mixed quantitative - qualitative approach, combining elements of systematic literature review and narrative synthesis. This dual strategy allows for both the identification of quantitative patterns, such as the distribution of research by technology, domain, or geographical area, and the qualitative interpretation of theoretical frameworks, educational models, and pedagogical practices.

The review was designed to answer the following guiding questions:

1. Technological Integration - How are emerging digital and immersive technologies (e.g., VR, AR, XR, Digital Twins, AI - based platforms) being integrated into education and training programs for critical infrastructure management?
2. Applications in Critical Infrastructure sectors - In which CI domains (e.g., energy, transport, water, healthcare, communication) are these technologies applied, and what are their objectives, methods, and measurable outcomes?
3. Applications in hazard contexts - In which hazard scenarios (e.g., natural, technological, or hybrid events such as earthquakes, floods, fires, or cyber incidents) are these technologies applied, and how do they contribute to enhancing preparedness, risk awareness, and adaptive response?
4. Stakeholders and target groups - Who are the primary stakeholder categories (e.g., operators, engineers, decision - makers, emergency responders, citizens) involved in these educational initiatives, and how are their learning needs differentiated?
5. Pedagogical frameworks - Which educational frameworks, instructional strategies, and learning models (e.g., experiential learning, problem - based learning, serious gaming) are most frequently adopted to support technology - enhanced training in CI resilience?
6. Skills and competencies - What competencies are prioritized in reskilling and upskilling programs for the CI workforce in response to digital transformation and system interconnectivity?
7. Research gaps and future directions - What knowledge gaps, methodological limitations, and research opportunities can be identified across CI sectors regarding the use of Educational Technologies for resilience - building?

These questions guided the structure of the analytical framework, enabling the mapping of technological and pedagogical trends across CI sectors and the identification of gaps in resilience - oriented education.



The configuration of clusters and connections was used to refine the final search query: central, well-connected clusters that intersect education, risk, and advanced technologies were prioritised, while loosely connected or isolated clusters guided the exclusion of domains outside critical-infrastructure-oriented training.

The search strategy utilised the bibliographic databases Scopus, Web of Science, and Google Scholar to ensure comprehensive coverage of the relevant literature. The search aimed to identify studies addressing the integration of educational technologies, immersive learning environments, and simulation - based training within the context of risk management and critical infrastructure resilience.

The search targeted titles and abstracts to ensure thematic relevance, and medical or biomedical domains were excluded to focus on engineering, environmental, and social applications related to critical infrastructures. The search was limited to peer - reviewed publications in English published between 2014 and 2025, corresponding to the decade in which immersive and digital learning technologies have rapidly evolved and been applied to resilience education.

9

“communication station”), thus generating noise in the search results. Conversely, the term training, essential within the educational scope, frequently occurs in computer science literature in reference to data training or machine learning pipelines, greatly expanding the retrieved corpus without contributing to the intended educational focus.

In parallel, while terms such as building or construction are overrepresented in the architectural and engineering literature, the expression critical infrastructure itself is notably underused in titles, abstracts, and keywords, even when the content clearly addresses systems that fall within this definition. To compensate for this semantic gap, the search strategy incorporated an extended list of sector - specific keywords (e.g., energy, transport, water, health, ICT, communication, industrial facilities) representing the main CI typologies recognized in international classifications. Although this strategy ensured broad coverage, it may have inadvertently excluded less conventional or emerging infrastructure categories.

This refinement of the search string was therefore an essential methodological step to balance recall and precision, ensuring that the corpus accurately reflected research positioned at the intersection of education, technology, and resilience, without being diluted by unrelated computational or construction - oriented studies.

The temporal window was defined to capture the decade of major expansion in immersive and simulation - based learning research. Initial screening was performed by reading titles and abstracts to ensure relevance to both educational and resilience domains, removing duplicates and off - topic entries before full - text analysis.

Despite these refinements, a certain degree of terminological variability remains intrinsic to the field of critical infrastructure studies. This linguistic heterogeneity, further discussed in Section 2.6 Limitations, inevitably affects retrieval precision and should be considered when interpreting the scope of the reviewed corpus.



Table1 - Domains and relevant keywords for search queries.

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
2015 - 2026 (PUBYEAR > 2014 AND PUBYEAR < 2027, inclusive)			
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

Drawing on the SNA mapping, candidate keywords are grouped into four domains: scenario-based education and training, immersive and interactive digital technologies, crises and natural hazards, and critical infrastructure/contextual settings. Table 1 consolidates these domains with representative keywords and search fields, translating the conceptual clusters into an operational Boolean query. This structuring sharpens the search strategy toward the intersection of training, advanced technologies, hazards, and CI contexts, while constraining retrieval from loosely related educational or engineering areas.

2.3. Inclusion and Exclusion Criteria

Studies were selected according to the following criteria:

Inclusion criteria:

- Peer - reviewed journal articles, conference papers, and book chapters focusing on education, training, or workforce development related to CI sectors (e.g., energy, transport, water, health, ICT);
- Studies presenting or analyzing the application of digital, immersive, or simulation technologies in educational or operational training contexts;
- Contributions explicitly addressing resilience, risk management, or system reliability in conjunction with learning methodologies;
- Research providing empirical data, methodological frameworks, or conceptual analyses relevant to CI learning ecosystems.

Exclusion criteria:

- Publications with a purely technical or engineering focus without educational implications;
- Papers not related to critical infrastructures or workforce development;
- Studies concerning medical, clinical, or COVID - related training;
- Non - peer - reviewed materials (e.g., reports, theses, or grey literature);
- Duplicates and documents not available in English.

Figure 3 summarises the screening process following PRISMA guidelines [17]. Using the four-domain query defined in Table 1, the database search retrieved 5635 records from three sources. After removal of 257 duplicates by DOI, 5379 records entered automatic screening; an abstract filter (4th domain) reduced this set to 2306 records (3073 excluded), and subsequent filters on subject area and publication year removed 22 and 469 records, respectively. Applying document-type and language criteria then excluded 128 non-article/non-conference items and 66 non-English records, leaving 1621 documents for manual screening. Title–abstract inspection discarded 992 items, resulting in 629 papers for full-text assessment, from which 524 were excluded because they did not provide substantive evidence on technology-enabled education or training in hazard-exposed critical infrastructure contexts. The final corpus comprises 105 studies included in the review (Figure 3), with full bibliographic details reported in Appendix A.

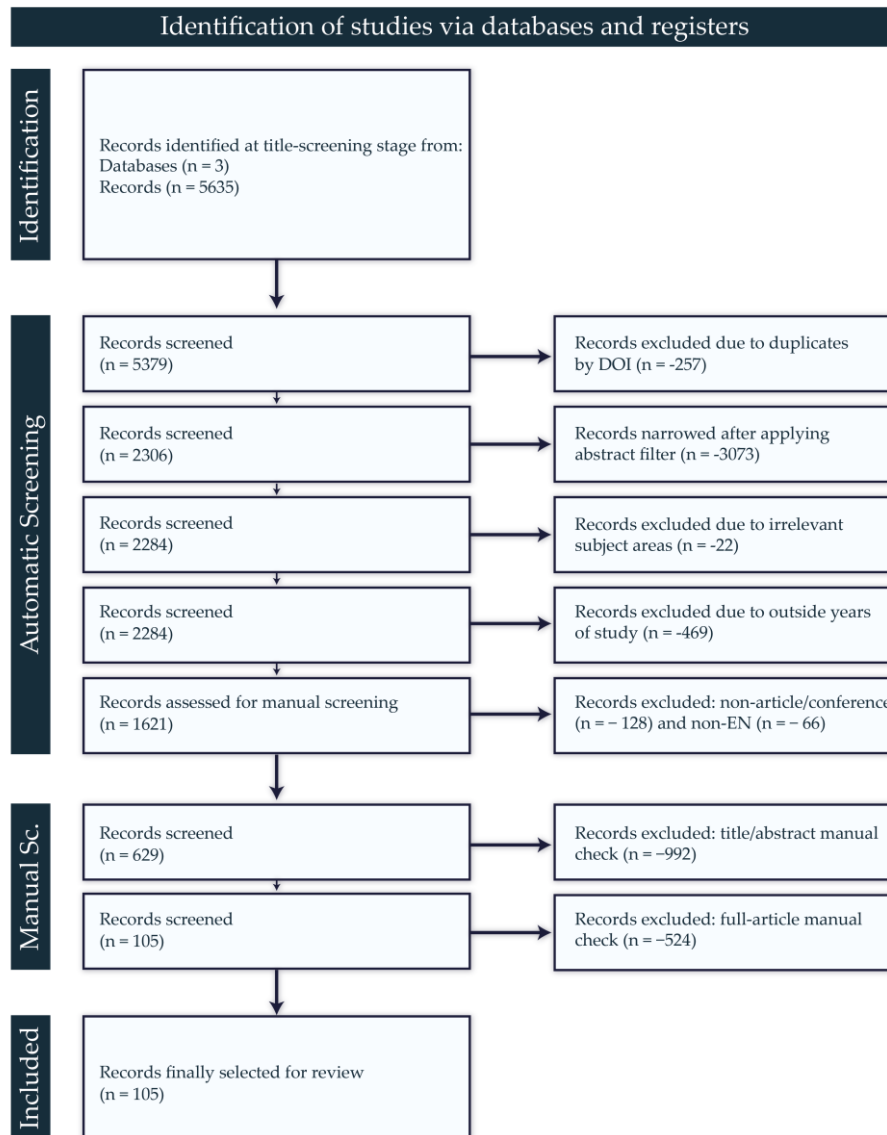


Figure 3: Overview of inclusion and exclusion criteria based on the PRISMA model

2.4. Data Extraction and Classification

Each selected study was reviewed and categorized 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);
- Infrastructure domain (e.g., transport, energy, water, health, communication);
- Stakeholders type (e.g., public authorities, industry operators, academia, civil protection);
- Hazard typology (e.g., natural, technological, cyber, or systemic);
- Implementation phase (planning, design, management, maintenance, or emergency response).

This classification enabled a cross - sectoral understanding of how educational innovation interacts with the operational and governance dimensions of CI systems and provided the foundation for the analytical framework discussed below.

2.5. Analytical Framework

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

- Descriptive analysis: mapping the frequency and distribution of studies by technology, sector, region, and hazard type;
- Thematic synthesis: identifying recurring patterns in educational approaches, instructional design, and technology adoption;
- Interpretative synthesis: connecting findings to broader discussions on digital transformation, sustainability, and resilience - oriented education.

This framework allowed both horizontal comparisons (across technologies and domains) and vertical interpretation (from empirical evidence to conceptual models), ensuring methodological rigor and conceptual depth in the synthesis of results.

2.6. Limitations

While comprehensive, this review presents several limitations that are inherent to the interdisciplinarity and linguistic complexity of the field. Despite the refinements introduced in the search strategy to filter out irrelevant uses of terms such as bridge, tunnel, or training, terminological ambiguity remains a structural limitation of research on critical infrastructures. The coexistence of engineering, educational, and computational vocabularies often generates semantic overlaps that complicate retrieval accuracy and reduce the precision of classification. Moreover, the expression critical infrastructure itself is still underused in titles and keywords, which may have resulted in the exclusion of relevant studies that nevertheless fall within this conceptual domain. As a consequence, the corpus analyzed should be regarded as representative rather than exhaustive. A further limitation concerns the rapid evolution of digital technologies, particularly Artificial Intelligence, holographic systems, and conversational agents, which may not yet be fully represented in academic literature. Publication bias toward English - language and peer - reviewed sources may also have limited the inclusion of grey or regional research.

Generative artificial intelligence (GenAI) tools, specifically OpenAI's ChatGPT, were used to support the development of this literature review. AI assistance was applied exclusively to the organization, synthesis, and comparative analysis of scholarly sources, helping to refine the academic writing style for clarity and consistency. All extracted information, interpretations, and conclusions were critically reviewed, verified, and rewritten by the authors to ensure conceptual accuracy, methodological rigor, and alignment with the research objectives. No GenAI tools were used to generate original data, figures, or experimental results, and the final content reflects the authors' independent intellectual contribution.

Overall, these limitations highlight the inherent challenges of conducting systematic reviews in interdisciplinary domains, where terminological variability and technological dynamism can affect both the breadth and depth of the retrieved evidence base.

3. DESCRIPTIVE OVERVIEW OF THE LITERATURE CORPUS

This subsection provides a descriptive and bibliometric overview of the reviewed corpus, offering a quantitative insight into the scope and dynamics of research on education and training for critical infrastructure resilience. It examines the typology of results, the chronological distribution of publications, geographical patterns of research activity, and the keywords most frequently associated with this domain. By mapping these dimensions, the analysis reveals how the field has evolved over time, where scientific contributions are concentrated, and which thematic directions are gaining prominence. The resulting overview establishes the empirical foundation for the following sections, which explore in greater depth the technological, infrastructural, and pedagogical aspects emerging from the literature.

3.1. Typology of results

The systematic literature review identified a total of 105 peer - reviewed papers from different regions of the world, highlighting diverse research strands on the application of immersive and digital technologies to critical infrastructure resilience and risk management. The research spans various subject areas, with Engineering, Computer Science and Social Sciences comprising significant portions of the literature. This interdisciplinary approach underscores the complex nature of natural hazard management and the diverse perspectives required for practical solutions.

3.2. Year distribution

Figure 5 illustrates the annual distribution of publications between 2015 and 2025. The line reports the total number of publications, while the stacked bars indicate, for each year, the relative contribution of journal articles and conference papers. Overall, the data reveal a progressive increase in research output over the period, with a pronounced rise from 2022 onwards, signalling growing scholarly interest in immersive technologies and their application to critical infrastructure resilience and hazard preparedness. The marked downturn observed between 2019 and 2021 may plausibly be linked to the disruptions caused by the COVID-19 pandemic, such as the cancellation or postponement of conferences and delays in publication and review processes.

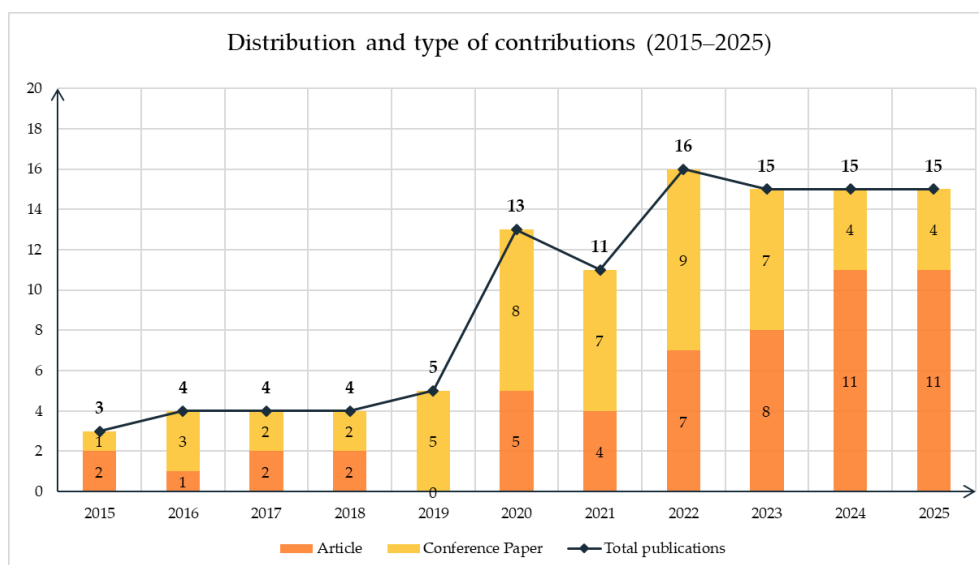


Figure 4: Documents by year. (Image created by the authors)

3.3. Geographical perspectives

The geographical distribution of the reviewed studies highlights three countries, China, the United States, and Italy, as the most active research poles in immersive learning for risk and resilience. Together, they account for nearly half of the analyzed corpus, confirming that research activity remains spatially clustered around a few key centers where technological capacity, institutional priorities, and hazard exposure intersect.

China leads this group, showing the highest concentration of studies focused on seismic, fire, and industrial hazards [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35]. 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 [23, 36, 37, 38, 39, 40, 41, 42, 43, 44, 46, 47, 48, 49, 50, 51]. 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 [52, 53, 54, 55, 56, 57, 58, 59, 60, 61]. Systems such as *BE-S²ECURE* [53] and *VRescue* [52] 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.

Overall, the corpus highlights how immersive training for critical infrastructures has developed through geographically distinct trajectories: hazard-driven experimentation in the Asia-Pacific region; multi-hazard and institutional integration in Southern Europe; increasing cross-regional convergence through industrial digitalization and human-factor approaches in Northern Europe; and data-driven pedagogy in North America. Despite these differences, a growing cross-regional convergence is evident in the shared ambition to embed resilience education within broader technological and institutional ecosystems.

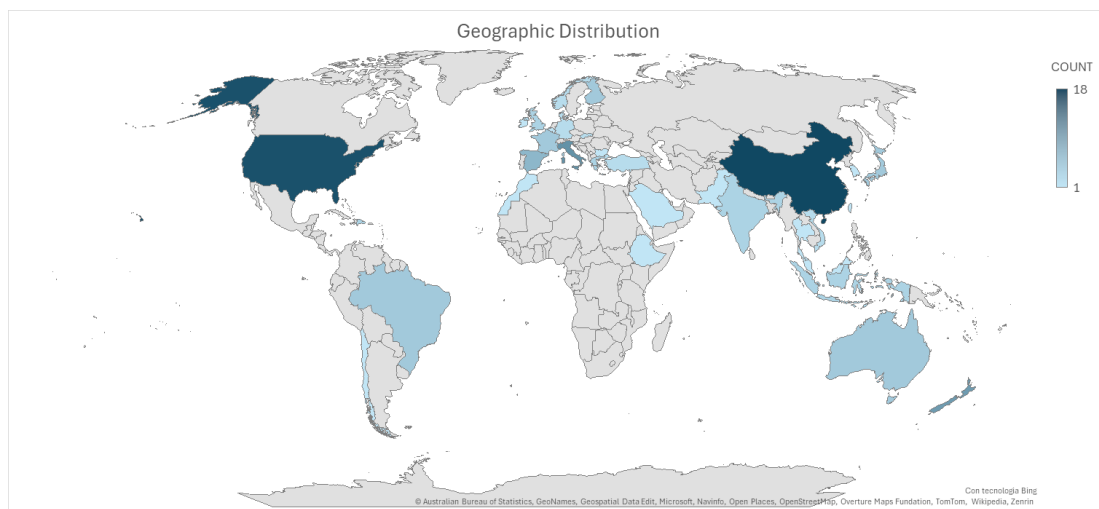


Figure 5: Geographic distribution of the reviewed studies. (Image created by the authors).

4. RESULTS

This section presents a critical synthesis of the reviewed studies, organized according to the six analytical dimensions introduced in the methodological framework. The multidimensional classification provides a structured basis for comparing diverse experiences, identifying technological and pedagogical patterns across regions and time periods, and mapping how emerging educational technologies are transforming the discourse on critical infrastructure resilience and training innovation.

4.1. Technological approaches

Training for the critical infrastructure management workforce increasingly relies on advanced learning technologies that combine immersion, interactivity, and adaptability. These systems enable experiential learning and feedback-driven practice, replicating the operational and cognitive complexity of real infrastructures and allowing both professionals and non-specialists to acquire technical, procedural, and behavioral competencies in safe yet realistic environments.

To compare heterogeneous experiences within the corpus, all reviewed applications were analyzed along two orthogonal technological dimensions.

- The Interaction Layer describes how users experience and operate within the system, ranging from non-immersive desktop- and web-based applications to fully immersive VR setups, mobile AR, and mixed - reality environments, up to multi-user metaverse platforms.
- The Simulation Engine Layer defines the computational logic and data back-bone driving system behavior, encompassing knowledge-based ontologies, Building Information Modeling, Digital Twins, Artificial Intelligence, Agent - Based Systems, Internet of Things integration.

Together, these layers delineate a continuum of technological sophistication: from analytical, model-driven desktop simulations to adaptive, data - enriched, and collaborative XR ecosystems, capable of embedding human learning within digital representations of operational infrastructures. Building on this framework, the following subsections examine the main interaction and simulation configurations identified across the reviewed corpus, highlighting how technological complexity aligns with educational intent and learning outcomes.

4.1.1. Interaction Layer

This section examines the reviewed studies according to their level of immersion and the interaction modalities between users and digital environments. Each degree of immersion determines the intensity of user engagement, the sensory and cognitive load, and ultimately the depth of experiential learning achieved. As illustrated in Figure 8, the interaction continuum ranges from non-immersive desktop solutions to fully immersive, and collaborative metaverse configurations.

The concept of the reality-virtuality continuum, originally introduced by Milgram [62], defines this progression, encompassing immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), 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.

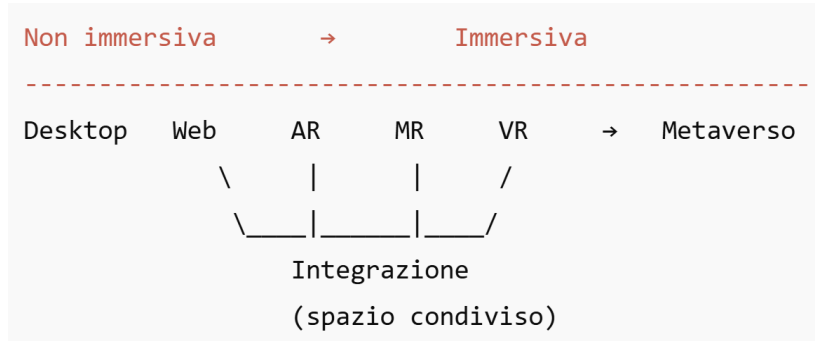


Figure 7: Reality–virtuality continuum

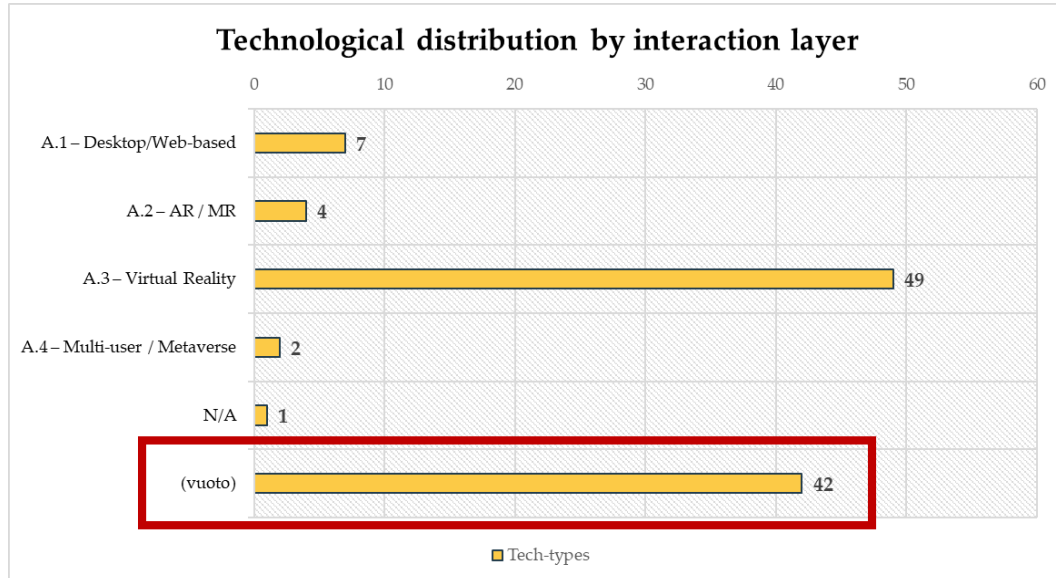


Figure 8: Distribution of technologies across the reviewed studies, classified by interaction layer. (Image created by the authors).

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4.1.1.1 Desktop and web-based

At the lowest level of the interaction spectrum, desktop- and web-based simulations represent the non-immersive analytical core of technology-enhanced learning for critical infrastructures. These systems deliver interactive 2D or 3D environments accessible through standard computers or web browsers, focusing on strategic decision-making, organizational coordination, and procedural rehearsal rather than physical embodiment. Their interfaces privilege clarity and accessibility over sensory richness, emphasizing how users interpret and control dynamic processes.

Desktop-based systems offer 3D visualization and interactive interfaces within a local computing environment, often employing dedicated rendering engines for high spatial accuracy and graphical fidelity. Among early applications Tian et al. [19] developed the Virtual City Earthquake Simulation Platform, a multi - module desktop environment that integrates 3D urban models (e.g. buildings, bridges, terrain, and street furniture) rendered with 3ds Max and V - Ray. Users can navigate the scene, trigger seismic events, and observe cascading effects such as fires, landslides, and infrastructure disruption. Interaction occurs via mouse and keyboard through an intuitive GUI, allowing the adjustment of parameters such as earthquake magnitude or evacuation routes. This system enables analytical engagement: observation, measurement, and interpretation of simulated impacts, making it suitable for planners and engineers involved in territorial risk assessment. Similarly, Nilsen et al. [18] present a 2D desk-top-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. [63] 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. [64] developed a hydropower - plant training platform where a control - room interface supports diagnostic and anomaly management tasks. The GUIDE2FR platform [65] 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. [66] propose a “dual hackathon” for flood event management, which integrates physical field exercises with a non-immersive digital support layer based on screens, drone video feeds, and shared information panels. Here too, the goal is not to recreate a substitutive virtual environment, but rather to amplify the collective readability of the situation through visual interfaces that can be accessed from standard workstations.

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. [67], which developed the Web - Based Tabletop Earthquake Exercise System. The platform operates at 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 with the system by defining resource allocations, selecting emergency response options, and assessing outcomes directly on shared maps. This multi-user interface reproduces the structure of real command chains, where different institutional roles coordinate through information dashboards and simulation playback. The system’s browser - based accessibility facilitates large - scale participation and cross - agency training, extending traditional tabletop exercises into interactive, data - driven environments. Instead of individual immersion, the focus lies on collaborative situational awareness and the ability to interpret, communicate, and act upon visualized information in real time. This mode of interaction reflects the logic of collective simulation, where users experience the model through decision coordination rather than sensory engagement. A closely related example is the Virtual Safety World developed by Shiradkar et al. [48], a multi-user 3D platform accessible from standard PCs that, in the context of fire - safety and evacuation training, compares a traditional slide - based safety training (SBST) with a first-person navigable “virtual world”. Although it remains fully non - immersive from a sensory standpoint, the system introduces avatars, interactive objects, and situated tasks, encouraging participants to rehearse procedures within a shared digital environment rather than merely observing static content.

Across these non-immersive, multi-user platforms, a recurring configuration emerges: a browser - or desktop-based delivery model, shared access to the same scenario, and a clear separation between simulation logic and the visual and interaction layer. The same pattern recurs in other desktop and web systems within the broader natural - hazard corpus. Building on these interface principles, several desktop and web-based systems maintain a distinction between a simulation core and a thin, configurable GUI layer. In the construction domain, the virtual construction safety framework proposed in [68] further exemplifies this approach, modelling 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 re-configured without modifying the underlying models [40, 69, 70]. 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. Visualisation 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 [41, 25]. 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 [71, 72]. 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 [41, 37, 73]. From an engine perspective, this preserves a clean architecture: the model computes state transitions, while a rule manager interprets them into feedback (scores, status colours, end - of - round re-ports) [74, 25]. The hazard domain changes across cases, but the pattern is stable: non - immersive systems are engineered as configurable, low - friction shells around a model, optimised for repeated use, batch comparison of scenarios and easy integration into classroom or workshop routines.

Overall, the desktop and web-based stratum of the interaction spectrum offers a non-immersive, GUI-centred mode of engagement oriented toward operational clarity, replicability, and shared control of scenarios and, as comparative evaluations suggest, can approach the cognitive effectiveness of more sophisticated XR configurations while maintaining minimal hardware requirements.

4.1.1.2 Augmented Reality - Mixed Reality

Intermediate levels of immersion are represented by Augmented Reality and Mixed Reality, which bridge the physical and digital dimensions of learning. Unlike fully immersive VR environments that detach users from their surroundings, AR and MR systems superimpose digital information onto real-world settings, creating hybrid experiences that preserve physical context while enriching it with interactive data. This duality makes them particularly effective for maintenance, inspection, and operational training, where spatial awareness and physical manipulation remain essential.

The reviewed literature reports several experimental applications of AR and MR technologies, often using *Microsoft HoloLens* or handheld mobile devices as interaction platforms [75, 24, 34, 76, 77, 27]. These systems merge hands-on practice with contextual visualization, allowing trainees to follow step-by-step procedures while maintaining full perception of the physical environment. Across the corpus, a coherent model of on-the-job procedural support emerges, in which digital overlays structure real-world action rather than simulate alternative environments.

Typical configurations include mobile AR modules coupled with 3D viewers for fire-rescue manoeuvres [24], or pre-flight inspection systems that convert checklists and manuals into multimedia content anchored to aircraft components [27]. 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.

Similar principles are applied in industrial and transport infrastructures, where AR overlays provide real-time guidance, hazard alerts, and diagnostics. MR interfaces extend these capabilities by synchronizing virtual annotations with physical components, supporting collaborative troubleshooting and remote supervision. Advanced MR systems focus less on immersion and more on precise spatial registration between digital and real elements, enabling coordination across multiple roles in complex scenarios. The *FightARs* platform [77] 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 [34] 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 [76] 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 [75].

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 [78, 79, 80]. 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 [43, 45]. MR headsets contribute spatial mapping directly on-device, ensuring that holograms remain anchored to real-world geometry [77, 34]. 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 [56].

Beyond individual use, co-present MR sessions enable multiple participants to view and manipulate the same spatially anchored content from different perspectives. Results consistently show that, while imposing a lower sensory load than VR, AR and MR configurations enhance situational awareness, self-efficacy, and procedural fluency by combining digital augmentation with physical context.

These hybrid approaches effectively reduce operational risk and improve the transfer of emergency strategies from simulation to real-world practice. By merging the sensory immediacy of physical environments with the scalability of digital overlays, AR and MR applications provide a foundation for collaborative learning scenarios and represent an intermediate step toward more fully immersive, multi-user metaverse ecosystems.

4.1.1.3 Virtual Reality

Among all the technologies examined, VR emerges as the most mature [81] and widely implemented modality in the analysed corpus. VR systems extend the concept of immersion by allowing users to interact with three-dimensional digital environments from a first-person perspective, combining visual, auditory, and kinesthetic feedback in ways that range from screen-based navigation to fully enveloping experiences. This flexibility makes VR particularly suited for reproducing complex and hazardous situations in CI, such as fires, tunnel incidents, plant failures, or urban evacuations, where direct physical training would be impractical or unsafe.

The reviewed applications encompass both gamified systems for behavioral and procedural training and non-game-oriented configurations, such as semi-immersive theatres and replay simulators, where the emphasis shifts toward observation, debriefing, and analytical reflection. Collectively, these approaches integrate visualisation, simulation, and interaction to support learning through action and reflection.

The following sections describe how these systems materialise across different levels of immersion; (i) non-immersive, (ii) semi-immersive, and (iii) fully immersive, each supported by specific device configurations and interaction modes. In addition, some studies propose hybrid arrangements, in which the same content can be accessed either in desktop mode or via HMDs, allowing adaptation to available resources and to the specific type of exercise.

Non immersive systems

Non-immersive VR applications are generally implemented in desktop mode, with 3D scenes displayed on standard monitors or large projection screens. These configurations, characterised by low physical engagement but high accessibility and scalability, are well suited for classroom use, rapid training iterations, and contexts in which hardware resources are limited. Interaction typically occurs through conventional input devices (mouse, keyboard, joystick) while still allowing users to explore three-dimensional environments, often encapsulated in simplified serious games. Despite the absence of sensory immersion, such systems have proven effective for training procedural reasoning, hazard identification, and decision-making under time constraints [61]. 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 optimised 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 prioritise scenario configuration and results interpretation while the engine manages geometric and physical computations [69, 70, 40, 41, 37, 82, 59, 83]. 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 [84] or in professional contexts such as firefighter training, exemplified by the *Fireman Rescue* simulation [85], emergency robot rescue training systems [22], and railway level-crossing safety applications [86]. Other examples include emergency preparedness scenarios based on large-scale virtual environments, such as the simulation of a terrorist attack in a train station [61], 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 [87, 47]. Examples include the *Second Life*-based 3D platform for university evacuation training [87] and the *Megacity CVE* environment, which provides a non-immersive version for PC-based evacuation exercises [47]. Cross-platform implementations expand these capabilities, maintaining desktop clients as default access points for urban-risk training [88; 89; 90; 91; 92; 30], or providing alternative interfaces for PCs and large-format displays [56; 49]. Across all these variants, non-immersive systems share a consistent architecture: 3D scenarios rendered on screens, standard input devices, and game or assessment logic handled through graphical interfaces, an approach that maximises accessibility, repeatability, and dissemination without imposing heavy technical requirements.

Semi - immersive systems

Semi-immersive configurations occupy an intermediate position between purely screen-based use and fully immersive VR systems. They exploit large-scale projections or enveloping displays to enhance the sense of spatial presence while maintaining physical co-presence among participants. In these environments, users share a collective field of view rather than wearing individual head-mounted displays (HMDs). Physical props and differentiated roles are often integrated, transforming the training space into a common scene for discussion, coordination, and decision-making.

Cylindrical or panoramic theatres equipped with multiple projectors exemplify this approach, immersing trainees in simulated emergency environments such as underground mining scenarios where rescue teams operate within a continuous visual field controlled by an instructor [93]. These systems foster shared situational awareness and teamwork, while a corresponding desktop VR version of the same content enables direct comparison between the two modalities. The cylindrical room enhances visual engagement and co-presence, whereas the desktop configuration reduces costs, motion sickness, and logistical constraints, making it more suitable for frequent training cycles and large audiences [93].

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 [51]. 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.

The same principle extends to CAVE (Cave Automatic Virtual Environment) systems, which project stereoscopic imagery on multiple walls to achieve high spatial awareness and collaborative immersion. In these room-scale configurations, participants can move freely within the physical space, making them suitable for behavioral studies and coordination exercises. This configuration has been adopted in various domains. As shown in Figure 10, one such implementation employs a hexagonal five-wall CAVE with continuous high-resolution projection and high-precision tracking of both participants and physical props, such as fire extinguishers, enabling realistic school fire preparedness training simulations [94].



Figure 1. Overview of the hexagonal CAVE VR environment.



Figure 2. Indoor fire simulation in the CAVE environment.

Figure 9: Example of CAVE-based application

In open-pit mining, Unity-based simulations reproduce quarry topography, elevation changes, and ambient soundscapes while logging individual and group performance [59]. 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 [95].

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 [96]. 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 [97].

Semi-immersive systems therefore complement rather than compete with fully embodied VR. They offer many perceptual and collaborative benefits of immersion without the sensory load or cybersickness associated with HMDs. Within the interaction continuum, these systems bridge single-station simulations and headset-based environments, offering a controlled and ergonomically sustainable framework for guided observation, collaborative decision-making, and the development of shared understanding, an approach that anticipates several of the multi-user and metaverse logics discussed later.

Fully immersive systems

Within the spectrum of interaction levels, fully immersive VR represents the configuration that most distinctly separates the user from the physical world. When wearing a head-mounted display, the real environment is replaced by a stereoscopically rendered virtual space, updated in real time according to head and hand movements. Six-degree-of-freedom (6DoF) tracking combined with controllers or hand-tracking systems enables first-person exploration, object manipulation, and interaction with diegetic interfaces, producing the experience of being *inside* the simulated environment rather than observing it externally. 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 [98, 99, 36]. 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 [100; 101; 37]. 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* [20, 21, 26, 31, 32, 35, 52, 55, 57, 58, 60, 102, 103, 104, 105, 106, 107, 108] or *Oculus Rift* [26, 106, 58, 47, 28, 109, 110, 111, 112, 113], 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 [31].

Standalone headsets, such as the *Oculus Quest* [114, 33, 50, 115, 116, 54, 42] and the *Meta Quest 2* [117, 118, 53, 113, 55], 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 [115; 94]. Their versatility also makes them suitable for field-oriented or multi-hazard applications requiring mobility and minimal logistical constraints [42, 53].

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 [119, 120, 121, 122], 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 [30, 57, 58, 87]. 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 [87].

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 [30]. 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 [57, 58]. 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 [95].

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 [60]. Through the integration of auditory, haptic, and motion feedback, these systems achieve multisensory congruence that strengthens spatial presence, situational awareness, and behavioral learning under realistic stress conditions.

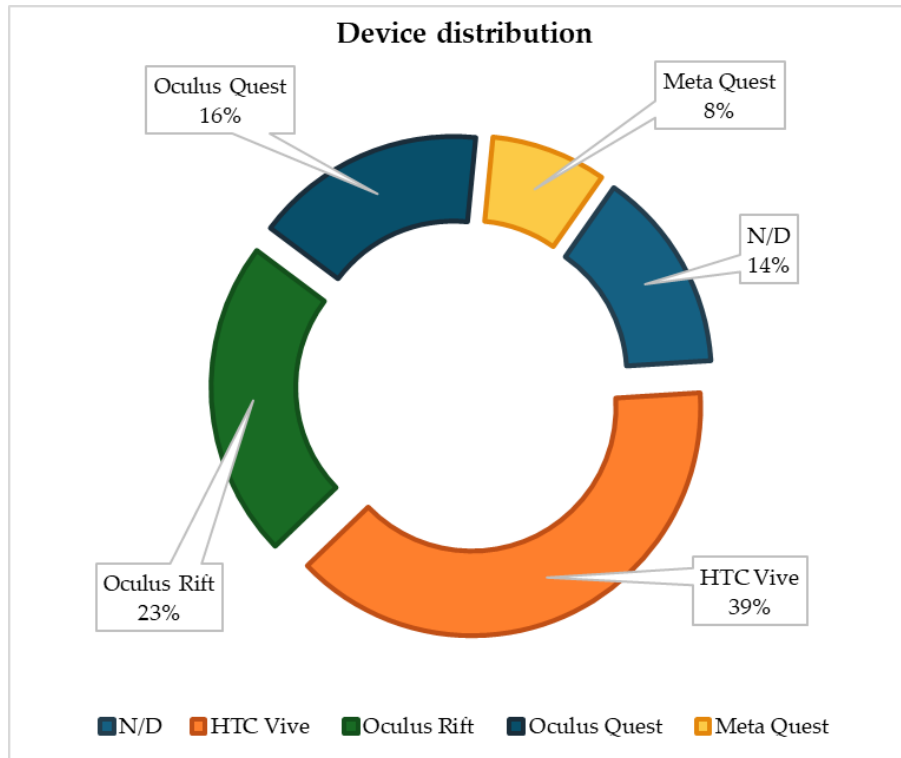


Figure 10: Distribution of devices in fully immersive VR studies with totally virtual environments. (Image created by the authors).

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 [30, 57, 58, 95, 107, 111, 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 practising coordination, victim search, and hazard mitigation [52, 57, 58].

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 [25, 36, 73, 69, 70, 40]. In the context of technological and NaTech risks, fully immersive environments reproduce industrial plants, refineries, and energy facilities to visualise 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 [30, 42, 60].

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 [31, 60, 109]. Educational and reflective applications [54, 112, 113] 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.

4.1.1.4 Multi User/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 visualise 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 [123]. 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 [39, 124, 125]. 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, 66]. 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 [126]. 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 [23].

In the context of emergency response, multi-user VR configurations also support collective practice in high-risk environments. The *VRescue* platform [52] exemplifies this approach, enabling simultaneous participation of rescuers and instructors within a photogrammetric reconstruction of a collapsed city. Similarly, the HCP–VR system [55] 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.

Collectively, multi-user and metaverse systems mark a paradigm shift from individual experiential learning to collective simulation, where knowledge is constructed through collaboration, negotiation, and shared awareness rather than isolated performance.

4.1.2. Simulation Engine Layer

The simulation backbone underlying each reviewed application reveals the evolution of learning technologies for critical infrastructure training, from early rule- based frameworks to more complex data-driven, adaptive, and cyber-physical systems.

Over time, the corpus reveals a clear progression: initial studies primarily codified emergency procedures through logical scripts, ontologies, and fixed rule sets, while more recent contributions integrate spatial data models, agent-based dynamics, and real-time information flows. This evolution progressively narrows the gap between training simulations and operational environments, transforming VR and XR systems from static demonstrators into dynamic platforms capable of reproducing behavioral, environmental, and infrastructural feedback in real time.

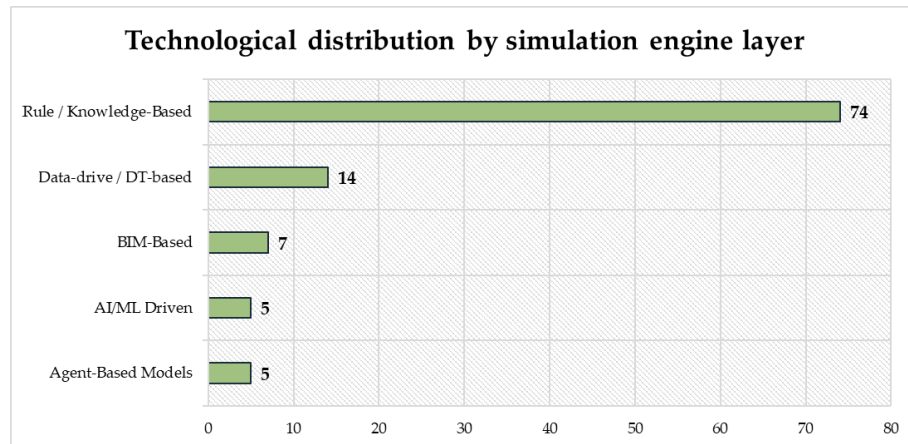


Figure 11: Technological distribution of the reviewed applications by simulation engine layer.
Image created by the authors.

4.1.2.1 Rule and Knowledge-Based Systems

The earliest generation of simulation environments in the corpus is characterized by rule- and knowledge-based architectures, where procedural knowledge and emergency actions are formalized through explicit scenario logic. These systems encode decision pathways as sets of predefined rules or ontological relationships, translating expert knowledge into structured models that can be replayed, audited, and validated.

Among the first examples of this category is a virtual simulation of a terror attack in a train station [61], which applies a clear sequence of rules to connect user actions with safety recommendations. Each action or mistake produces a corresponding reaction, such as feedback messages, warnings, or corrective instructions. The experience is entirely governed by predefined if–then relations that regulate what happens when the player encounters smoke, debris, or fire. In this way, the simulation works as a chain of cause-and-effect episodes that reproduce the logic of procedural training, forming one of the earliest demonstrations of a knowledge-based simulation engine.

Another notable instance of this approach is the *Web-Based Tabletop Earthquake Exercise System* [67], which operates at the territorial scale. The platform applies hierarchical logic to model decision chains across provincial, municipal, and county authorities: each user's choice, resource allocation, communication flow, or intervention timing, triggers algorithms that propagate consequences through the simulated administrative network. The resulting architecture mirrors real command hierarchies, transforming decision-making into a process of strategic reasoning rather than an immersive sensory experience.

In more recent literature, analogous rule- and knowledge-based logics are adopted across numerous application domains, where simulators and serious games translate technical standards, 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 [22, 31, 89, 109, 117, 120]. 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 [59, 93]. 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 [75, 118], 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 [26, 30, 92, 114, 122, 126]. Related studies extend the same principle to fire safety and evacuation training [20, 77, 85, 91, 102, 110, 115, 119], construction safety [32, 33, 83, 88], healthcare and emergency preparedness [46, 106], aircraft emergency procedures [90], photovoltaic and power-plant systems [29, 64, 96], and XR training for confined spaces [56, 60], showing that rule- and knowledge-based logics remain central to the modelling 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 [86].

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 [112], to vary resource availability and avatar roles in motivational experiments [18, 57, 58], and to guide teacher and student responses during school evacuation drills [21, 48, 76, 84, 94, 97, 116]. The same logic governs mission flow and scoring in professional rescue simulations such as *VRRescue* [52]. More recent developments reformulate this rule-based structure into adaptive frameworks, such as the “spiral narrative” introduced in [113], where feedback loops and scenario restarts support reflection-in-action and incremental learning.

Across these implementations, rule-based systems have evolved from static scenario sequencing to dynamic narrative frameworks capable of blending behavioral control with pedagogical adaptability. Hazard-oriented applications continue to rely on similar logic, encoding mission steps, scoring rules, and error conditions as finite-state machines or runtime rule tables [41, 37, 73]. Instead of simulating behavior from the bottom up, these engines apply *if–then* relationships to discrete events, guaranteeing predictable scenario flow and facilitating validation when training must comply with formal safety or operational protocols.

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 [74, 38, 121]. 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 [104], on evacuation times and routes [87], on risk scenarios in urban construction sites [51], on checklists for pre-flight safety inspection [27], on the construction sequence of wind towers modelled through mathematical procedural animation [50], on risk and emergency response procedures tested in a hackathon focusing on real flood scenarios [66], on safety pathways grounded in hazard recognition [49], and on simulated operations in gas power plants that follow codified EPR/HSE logics [103]. 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 implementations, such as *HCP–VR* [55], apply the same principle through dual guided and evaluated modes, where encoded procedural rules drive feedback, error detection, and task sequencing in high-capacity pumping operations for civil protection training, demonstrating how traditional rule-based logic can be embedded within immersive procedural simulators. Technologically, this architecture maintains conceptual clarity and traceability, making it possible to directly map policy changes or revised procedures onto the corresponding logic within the training engine.

4.1.2.2 BIM-based

As simulation technologies matured, attention shifted from abstract procedural logic to spatial and architectural realism. Depending on the infrastructure typology and lifecycle stage (design phase, existing asset, or hypothetical model), different strategies can be adopted to represent geometry, materials, and semantics within immersive simulations. The integration of Building Information Models with game engines plays a central role in this evolution, particularly for existing buildings where digitization products such as 3D scans or Revit models can provide highly detailed architectural (e.g. building element material, pieces of furniture, lighting conditions and evacuation systems) and semantic representations. However, “integrating BIM” rarely means transferring the full information model: it is more often a selective curation process, where semantics are reduced to what is actionable in real time, while properties crucial for simulation (e.g., physical parameters for fire/smoke or crowd dynamics) require additional mappings or simplifications. This creates a recurring 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 [28, 96]. 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 [82]. 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 [28]. 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 [68]. 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 [32].

This approach is exemplified in the Auckland City Hospital studies [95, 111], 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 [107], 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).

In this context, BIM is not merely a geometric reference but a semantic data backbone – yet in many of the reviewed cases this “backbone” is effectively a minimal, fit-for-purpose semantics (IDs, categories, a small set of properties) that enables scripting, while richer BIM semantics are either discarded or manually reconstructed to become operational in real time. The consequence is that the apparent informational completeness of BIM can mask strong assumptions about what truly matters for training and about which phenomena (fire/smoke, human behavior, operational dynamics) are actually being modeled. This integration demonstrates how architectural accuracy and procedural fidelity can coexist, transforming digital building models into interactive training infrastructures. 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 [68]), the more it becomes sensitive to data quality and governance. Conversely, highly operational pipelines such as the tunnel workflow [28] 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. Despite the broad consensus on the pedagogical value of BIM–VR integration, several technical

challenges persist. BIM datasets often contain large volumes of information and may lose material attributes or textures during conversion to real-time engines. To maintain usability, most studies highlight that training-oriented BIM models do not require engineering-level detail but must ensure perceptual credibility and behavioral validity. Balancing computational efficiency with visual realism remains one of the key frontiers in developing immersive digital-twin environments for education and operational resilience.

In parallel, BIM-based engines provide a structured way to reuse design - time information in interactive training. Pipelines that export Revit or IFC models to game engines perform a sequence of transformations: mesh decimation, collider generation, occlusion setup and material substitution [28]. 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. This creates new opportunities for scenario scripting: all emergency exits, extinguishers, or signage elements can be queried and manipulated collectively, or compliance between planned and simulated wayfinding can be dynamically verified. Technologically, this approach transforms BIM from a static repository into a living database that immersive engines can interrogate and adapt for training – yet such “liveness” is not automatic: it depends on verifiable pipelines, update rules, and validation metrics. Without governance (BIM versioning, export consistency, controlled attribute loss), the system risks producing a twin that is visually credible but semantically impoverished, where procedures are correct “in the engine” more than in the real world.

4.1.2.3 Agent-Based Models

A further conceptual leap in simulation design is represented by agent-based modelling, which introduces collective behavior and crowd dynamics into immersive training environments. This paradigm shifts the focus from individual procedural actions to the emergent properties of many autonomous entities interacting under shared environmental constraints.

Within the corpus, this approach is exemplified by the *BE-S2ECURE* platform [53], which integrates physical hazard models such as earthquake and heatwave dynamics with agent-based simulations of human evacuation. By coupling environmental and behavioral layers, the system evaluates how spatial configuration, exposure, and human response jointly influence resilience performance. In educational terms, agent-based simulation bridges the gap between architectural design and behavioral science, enabling participants to understand how environmental structures affect collective outcomes and emergency decision-making.

A second notable example is provided by the study Sharma et al. [47], which adopts an explicit Agent-Based Modeling and Simulation (ABMS) engine for evacuation in virtual reality. In this case, overall crowd dynamics emerge from the interaction of multiple autonomous entities – avatars and computer-controlled agents assigned hostile, non-hostile, leader-following, selfish, or goal-following roles – governed by local decision rules, multi-level crowd-behaviour strategies (ViCrowd: rule-based/reactive and group-based), and waypoint algorithms that drive movement towards evacuation goals rather than predefined procedural scripts.

Complementing object-centred approaches like BIM, agent-based engines model behaviour through sets of local rules applied to autonomous entities. Each agent perceives its surroundings, reacts to stimuli, and interacts with other agents based on probabilistic or heuristic rules. In participatory flood-simulation environments, a dedicated agent-based module governs individual responses while a hydrodynamic component calculates water movement and environmental change [124, 39, 125]. The overall architecture is typically organised into three layers: the spatial substrate, the behaviour rules and the human interface. Facilitators and participants interact primarily with configuration parameters, while the simulation engine manages agent evolution and aggregates outcomes for analysis or debriefing.

This modular design is technologically advantageous because it allows the same behavioral core to support both training and analytical experimentation. Changing the interface or logging strategy converts the platform from a participatory educational tool into a quantitative model for scenario testing. By linking individual decision-making to collective behavior, agent-based systems thus enable the exploration of cascading effects, coordination challenges, and resilience strategies within complex, dynamic infrastructures.

4.1.2.4 AI and ML Driven Systems

Parallel to the emergence of rule-based and agent-based approaches, a new generation of serious games introduces artificial intelligence (AI) and machine learning (ML) to personalize the training experience and enhance system adaptability. AI-driven adaptation enables the simulation engine to continuously assess user performance, adjusting parameters such as task difficulty, feedback frequency, and pacing to maintain engagement and prevent cognitive overload.

This principle is implemented in the Adaptive Serious Game for Emergency Evacuation [54], 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 [42], 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.

Together, these systems mark a transition from fixed scripting to machine-guided learning, in which the simulation responds to the trainee's evolving skillset and situational awareness. Instead of predefined sequences, the experience becomes a dialogue between user and algorithm, driven by data and behavioral feedback loops.

Further along the data-driven spectrum, AI and ML components appear as embedded services inside some engines rather than as visible features. Flood-susceptibility tools, for instance, train classifiers on spatial predictors and then ship the trained model as a callable module; the viewer requests susceptibility values at runtime and displays them as colour fields or height maps. Similarly, adaptive-training platforms log user actions and derive difficulty adjustments or pacing decisions through learned mappings, without changing the art assets or scene graphs [32, 121]. From an engineering perspective, these ML components function as black-box models with defined input–output contracts, simplifying integration but raising questions of explainability when transparency is essential to the learning process.

At the opposite end of this spectrum, some systems employ AI/ML models as the actual decision-making core of the training engine. On the one hand, in the context of evacuating educational buildings in a metaverse environment, a guidance agent trained via Deep Reinforcement Learning (rainbow DQN) is deployed on top of a social force model, transforming the state of the environment into discrete actions on dynamic guidance signs with the goal of minimizing overall evacuation time [23]. On the other hand, in fire-rescue skills training, artificial intelligence is implemented as a hybrid optimization and risk-assessment pipeline, in which Particle Swarm Optimization algorithms compute intervention paths based on an explicit fitness function, and a data-driven risk assessment framework – combining fuzzy comprehensive evaluation, Monte Carlo simulation, AHP, and Bayesian networks – dynamically updates risk indices from historical data and training logs [24]. Conceptually, the former exemplifies a model-free policy learning approach for controlling evacuation strategies, whereas the latter represents a model-based setup in which optimization and probabilistic inference are tightly integrated into the rescue training scenario.

The integration of AI and ML within training simulations thus reflects an ongoing convergence between data analytics and pedagogy. By combining predictive modelling with behavioral adaptation, these systems move toward continuous, evidence-based learning cycles that align simulation complexity with user competence and operational goals.

4.1.2.5 Data Driven and Digital Twin Systems

The most recent and technologically advanced simulation environments are built on data-driven and digital-twin architectures, where training and operation progressively converge. In these systems, simulation engines are dynamically linked to structured datasets, sensor inputs, or analytic modules, creating adaptive learning environments that mirror the logic of real infrastructures.

The Virtual City Earthquake Simulation Platform [19] represents an early precursor of this approach. Its multi-module architecture integrates 3D urban data, hazard parameters, and interdependent infrastructure networks, enabling comparative analysis of seismic impacts and cascading failures. This modular design anticipates the principles of digital twins, where each component of the city (terrain, buildings, and lifeline systems) can be parameterized and recombined for different training and analytical purposes.

Following the same trajectory, integrated XR–DT frameworks such as *GUIDE2FR* [65] unify digital-twin representations with IoT sensing and live video feeds, augmented by machine-learning modules that forecast environmental variables. *GUIDE2FR* operationalizes this coupling through a geolocated, web-delivered building twin continuously updated from heterogeneous sensing, where threshold-based semantic layers and dashboards expose the live state of the facility and support situational interpretation. A multistep ML forecasting layer predicts selected environmental indicators from drill data, enabling predictive monitoring rather than static visualization [65]. 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 [26, 75]. These applications connect BIM, GIS, and IoT data streams to support immersive maintenance rehearsal, safety training, and predictive asset management, thereby linking operational analytics with human performance. A closely related DT pattern is reported for safety training in automated production environments, where real-time synchronization merges machine/cell telemetry with human indoor positioning into the VR runtime via robotics middleware and VR clients, enabling live testing of safety zones and stop conditions [105].

A parallel development can be observed in the locomotive crew VR training environment proposed by Gao et al. [35], which merges CAD-based mechanical modelling with Unity3D simulation engines to create an interactive, data-driven learning twin. The platform links real-time operational fault diagnostics with immersive instruction and automated assessment, illustrating how digital-twin logic extends from industrial operations to vocational training contexts. In the same line, the EGCERSIS simulation engine [108] couples a digital twin of a metro station with a decision-support core capable of processing sensor data and user actions in real time, transforming crisis scenarios into adaptive, data-driven exercises that integrate immersive visualization with procedural analytics. A further data-driven training twin is achieved when real site states are re-played into the virtual environment: *VirtualSafeConDM* [68] reconstructs training scenes from as-built digital models and measured movement traces, instantiates and updates hazard/protective zones based on safety-rule geometry and observed positions, and logs zone interactions as structured incidents exportable for post-hoc behavior analytics.

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 [25]. 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 [99, 36]. 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 [121].

Data-driven logics also underpin emerging emergency-response twins, where photogrammetric reconstructions and AI-assisted routing transform virtual environments into operational proxies. In rescue-training systems such as *VRescue* [52] and *VRescuer* [42], immersive simulations are linked to performance data, route optimization, and environmental variability, enabling continuous feedback and analytics-based decision support. DT-oriented derailment training frames the twin as a coupled architecture spanning the physical system, its virtual counterpart, a unified data layer, and service modules: field data are used to drive simulation and rescue-plan validation, while physics constraints and collision checks support operational decision workflows [34].

In this category, probabilistic Bayesian event-tree engines such as *BET_UNREST* are executed alongside volcanic unrest exercises to update eruption scenarios and inject structured forecasts into the training flow [71]. Similarly, tsunami inundation solvers have been coupled with school evacuation drills, generating composite scenario movies that allow experts and citizens to iteratively test and refine evacuation strategies [72].

At the architectural level, metaverse-labelled 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 [123, 56].

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 [28]. 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.

Overall, data-driven and model-integrated systems mark the transition from visual fidelity to functional intelligence in training design. By connecting information modelling, sensing, and human interaction, they enable the emergence of living digital twins, adaptive, evidence-based environments that strengthen both technical accuracy and human preparedness across the full spectrum of critical-infrastructure domains.

4.2. Pedagogical Approaches

Training for critical infrastructures goes beyond procedural repetition: it relies on pedagogical architectures capable of transforming simulation into authentic learning experiences. Across the reviewed studies, learning does not occur within virtual environments, but through them - at the intersection between technological mediation and cognitive construction. Immersive technologies and serious games reveal this common intent through a continuous process of learning through action, reflection, and adaptation. This section follows that trajectory: from experiential and situated learning, through structured, game - based frameworks, to reflective and adaptive learning ecosystems that sustain long - term competence and resilience.

4.2.1. Experiential and Context-Based Learning

At the foundation of all immersive education lies experiential learning: knowledge is built through action, perception, and situated engagement rather than abstract instruction. By placing participants in realistic operational contexts, such as hospitals, industrial facilities, or urban areas, these systems reproduce the complexity of decision - making under stress. In earthquake - related applications, for instance, Lovreglio et al.[95] and Feng et al. [111] 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 [127] 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 [98; 99; 36]. 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 [78; 79; 80; 77]. This experiential grammar combines guided exploration, embedded visual cues, and structured autonomy, bridging the gap between knowing and doing [128, 129] and building perceptual awareness, procedural fluency, and adaptive response. In training for critical infrastructures, experiential learning therefore provides the ground layer of competence: it builds perceptual awareness, procedural fluency, and the ability to respond adaptively to evolving operational conditions.

4.2.2. Serious Games as Structured Learning Environments

Building on experiential learning principles, Serious Games represent a structured pedagogical modality that integrates narrative design, feedback systems, and interactive challenge into coherent learning frameworks. Rather than serving as mere add-ons to simulation, SGs constitute self-contained learning environments that translate technological affordances into rule-based, emotionally 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) [130] to the design of an emergency-preparedness simulation in a train-station terror attack scenario [61]. 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, 20, 21, 22, 26, 28, 29, 30, 31, 32, 33, 42, 47, 49, 52, 53, 54, 57, 58, 59, 60, 61, 75, 82, 83, 84, 85, 86, 88, 89, 90, 91, 92, 94, 95, 102, 103, 104, 105, 107, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 126].

These environments combine realistic operational settings with structured objectives, feedback loops, and progression mechanics that reinforce decision-making and procedural reasoning under simulated stress. Participants navigate complex scenarios, perform critical operations, and experience the consequences of their choices, practicing evacuation strategies, hazard identification, maintenance protocols, or emergency coordination across domains ranging from education and healthcare to transport, energy, and process industries.

Through their ability to synchronize the engine layer (the logic of rules, feedback, and system behavior) with the interface layer (the domain of perception, action, and emotion) SGs embody what can be defined as a pedagogy of the virtual: a cognitive and emotional space where knowledge is enacted through interaction, experience, and reflection. This synthesis of structure and immersion positions SGs as a central mechanism for translating technological sophistication into meaningful, evidence-based learning for safety and resilience.

The pedagogical architecture proposed by Gao et al. [35] 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 is the backbone of serious - game pedagogy, providing a temporal and emotional framework for learning. Across the reviewed corpus, SGs adopt a variety of narrative structures and pedagogical mechanisms that reflect different training objectives and learner expertise.

- Linear narratives, common in early applications [95, 111, 112], 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 (53, 54, 107);
- Reflective storylines, exemplified by spiral or feedback - driven narratives, integrate reflection - in - action through iterative redo cycles [113].
- Mission - based storylines immerse participants in task - oriented operations, such as urban rescue and rescue or evacuation drills, emphasising teamwork, situational awareness, and leadership (52, 97). Structure decision episodes allow learners to observe the consequences of their choices over a small number of scenes [74, 37, 38].

These structures sustain cognitive flow [131], 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 [132], 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. [113] and Rahouti et al. [54]

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 emphasise procedural clarity [41; 37; 73]. Immediate feedback - through scores, status changes, or corrective prompts, refinement across multiple iterations [74; 101; 32]. 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

Regardless of the degree of immersion, most VR - SGs present progressive, self - contained scenarios within a storyline. In terms of interaction, users generally operate from a first-person perspective, viewing the scene through the eyes of the virtual character. This perspective is considered the most appropriate for enhancing embodiment, particularly in view of the non-immersive application, and teleportation was chosen as the movement solution. 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 [87]. Some studies [60, 106] 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 [106]. 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. The pedagogical relevance of interactivity is further supported by comparative research on emergency-preparedness simulations [61], which contrasted interactive and non-interactive versions of the same scenario. This investigation demonstrated that active participation produced higher emotional arousal, perceived threat, and self-efficacy, key variables of the Protection Motivation Theory, than passive observation. These results highlight that behavioral engagement and control of action are as crucial as sensory immersion in shaping learning effectiveness and emotional resonance during safety training.

Navigation mechanics are designed according to the context of use: teleportation, or movement between fixed points, is generally preferred in wide or complex environments to prevent disorientation and motion sickness, while free locomotion is adopted in smaller or task - focused scenarios where user behavior needs to be monitored.

Non-Player Characters (NPCs), entities not controlled by users but by predefined scripts or autonomous behaviors, play a crucial narrative and functional role within immersive training environments. Their inclusion adds social realism and behavioral complexity, allowing users to interact within dynamic virtual ecosystems that mirror human interactions typical of the critical infrastructures. 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 [95]; in post - earthquake operations, they act as victims or rescuers, generating realistic and dynamic contexts for team training and crowd management [52, 42, 53]; in educational environments, they serve as instructors or peers who provide guidance and feedback [112]; and in industrial or confined - space scenarios, they function as virtual supervisors assisting with procedural operations [60]. 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. [95], 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. Such details significantly improve the sense of presence and emotional engagement, transforming VR environments from static

simulations into interactive narrative spaces. Within the storyline structure of serious games, NPCs serve both as narrative anchors, guiding the progression of events, and as instructional agents, delivering contextual information or corrective feedback during training. By integrating scripted social interactions, they foster cognitive immersion and empathy, encouraging users to interpret complex situations rather than simply executing pre-defined tasks. Ultimately, the inclusion of NPCs bridges the gap between procedural learning and human - centered experience, reinforcing the pedagogical realism of immersive simulations across all 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. [107] integrate dynamic difficulty adjustment and personalized feedback to sustain learner motivation and inclusion, in line with Universal Design for Learning (UDL) principles [133]. 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 [101; 32; M_067]. 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 [41; 73]. 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 [134], as discussed by De Lorenzis et al. [55], whereby temporary guidance structures are provided and gradually withdrawn as competence and autonomy increase. Similarly, the VR training platform by Gao et al. [35] incorporates adaptive guidance and assessment functions that adjust to the user's performance level. By analysing task completion, accuracy, and response time, the system dynamically adapts instruction and feedback, ensuring that both novice and experienced operators benefit from tailored learning experiences within the same immersive framework.

Feedback and Debriefing

Feedback mechanisms are structural to SG pedagogy. Evidence from [112] indicates that post - game reflection results in the most significant learning gains, and complementary findings from [107, 113] 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 [61]. Structured debriefing modules, including action logs, replays, and performance dashboards, support self - analysis and instructor facilitation [37; 38; 80]. 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 [135] and reflection - in - action during the exercise itself. Debriefing sessions, replay functions, and instructor - mediated discussions [37; 80; 38] 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 [95, 113] 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 [99; 36 38]. 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 (52, 58; 57). These configurations promote distributed situational awareness and collective intelligence, aligning with contemporary theories of social learning [129]. 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 in highly dynamic and uncertain environments, where multiple hazards - both natural and anthropogenic - can significantly disrupt their performance, safety, and service continuity. In rethinking how critical infrastructure is taught, hazards must be understood not as background variables but as the initiating forces that drive disruption and shape decision - making contexts. They define the conditions under which systems fail, adapt, or recover, and thus provide the foundation for effective preparedness and response training.

In the literature, hazards are broadly classified into Sudden - Onset Disasters (SUODs) [136] and Slow - Onset Disasters (SLODs) [137]. 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 [138], providing consistent terminology for triggers, footprints, and impact sequences, that support clear learning objectives. The Comprehensive School Safety Framework [139] 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 [140]. Compound and cascading risks such as storm - then - flood sequences require training to reflect real world escalation patterns [141]. Natural Hazard Triggering Technological Disasters (NaTech) events, where natural hazards trigger technological failures, and cascading interdependencies across systems [142] further complicate the operational landscape and must be explicitly incorporated into education and training frameworks.

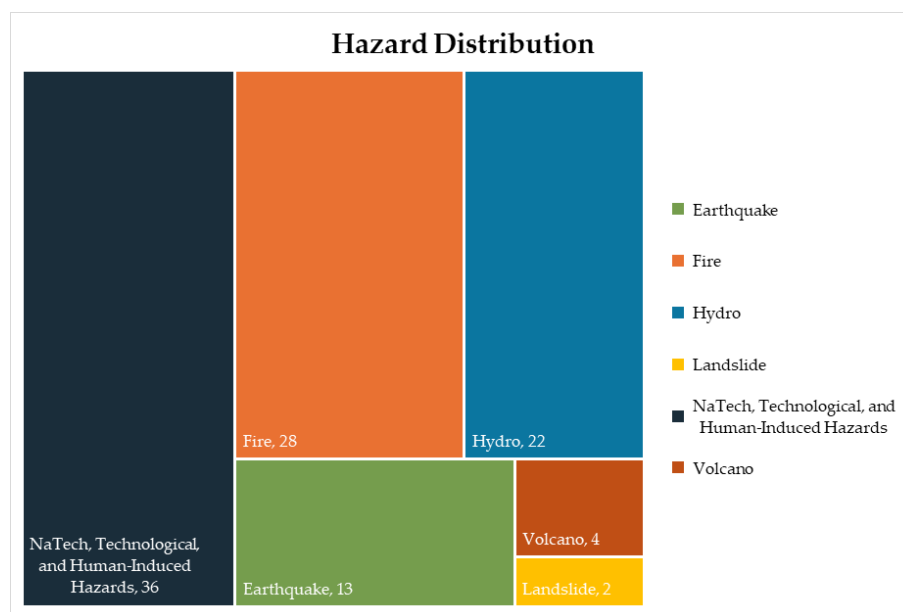


Figure 12: Distribution of hazard types across the selected papers. (Image created by the authors).

The distribution of hazards across the selected literature shows earthquakes as the most frequently addressed, followed by floods and fires, with other hazards treated in more specialized studies. To enable comparability across hazard types, each is analysed through a shared analytical framework that links the scientific logic of the phenomenon with its pedagogical and technological translation into simulation and immersive learning environments. For each hazard, four complementary dimensions are examined: (i) Objective - the educational and operational aims associated with understanding and managing the specific hazard; (ii) Applications - representative cases and training implementations drawn from the reviewed literature; (iii) Representation of the phenomenon - the models, simulations, and digital tools used to make the process visible and actionable; (iv) Limitations - current constraints, unresolved challenges, and transferability gaps between simulation and real - world performance.

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 [99; 36; 100; 43; 45; 74; 80; 40; 41; 25; 101; 123; 37; 72; 73; 38; 124; 39; 125; 56, 66]. A shared objective is to link rainfall, wind and water - level dynamics with concrete consequences for people, buildings and infrastructure, so that users can recognise 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 [40; 41; 37; 73]. Other tools target communities and planners and aim to support understanding of how defence portfolios and land - use choices shape inundation, damage and service disruption in specific catchments and cities [25; 36; 38; 124; 39; 125; 56, 66]. Technical simulations seek procedural competence for constructing and deploying mobile flood barriers under time pressure [101].

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 [99; 36, 96]. Tsunami tools link inundation maps and evacuation scenarios to help users understand run - up limits, arrival times and safe areas [100; 72]. Tropical cyclone and hurricane games focus on preparedness and response, training learners to interpret forecast products and plan resources ahead of landfall [74; 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 [40]. 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 [41; 37; 73]. Sea-level rise and coastal flooding experiences support climate-change teaching and adaptation debates in higher education and outreach programmes [99; 36]. 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 [43; 45; 80]. Tsunami simulations appear in school lessons and evacuation drills, where they underpin practice on route choice and timing [100; 72].

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 [41; 25; 36; 38; 124; 39; 125; 56, 66]. Immersive digital-twin frameworks show flood propagation over detailed terrain and help technical staff rehearse monitoring and warning procedures using synthetic or replayed events [25; 36; 38]. In operational contexts, the HCP-VR system [55] 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 practise assembly and deployment sequences under varying hydraulic conditions [101].

Hurricane logistics games support humanitarian and civil-protection personnel in rehearsing pre-positioning and routing decisions under uncertain forecasts [74].

Representation of the hazard phenomena

Inland flood representations range from conceptual models to data - driven simulations. In school -centred 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 [40]. Web - based games such as FloodGame use stylised 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 [41; 37; 73]. 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 [25; 36; 38; 56].

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 [99; 36]. Prototype systems for urban-scale tsunami evacuation similarly rely on 360° panoramas of real neighbourhoods, 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 [96]. Tsunami education tools use numerical inundation modelling 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 [100; 72]. 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 [124; 125; 56].

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 [43; 45]. 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 [74]. Here the focus is on path, intensity and forecast uncertainty rather than detailed damage mechanics.

Limitations

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 [99; 36; 100; 72]. 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 [41; 37; 73]. Work that frames flooding as risk assessment does foreground likelihood and consequences but still relies on deterministic model runs once inputs are fixed [40].

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 [25; 36; 38; 56]. Many serious games simplify hydrometeorological processes to reduce learning barriers and hardware demands, which suits awareness - raising but restricts operational use [41; 37; 73; 66].

The link to critical infrastructure performance remains partial. Several tools include roads, buildings and simple defences but lack explicit modelling of interdependent networks or cumulative damage from repeated events [41; 25; 36; 38; 124; 39; 125]. Training on mobile flood barriers concentrates on local deployment and does not propagate barrier performance into system - scale consequences [101]. Participatory simulations highlight trade - offs between measures and residual flood risk but seldom extend to detailed models of transport, energy or water systems [124; 125; 56, 66].

4.3.2. Landslide

Objectives

The landslide studies focus on rainfall - induced slope failures and their consequences [69; 70]. 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 [69; 70]. 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 [69; 70]. 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

Hazard is represented through responsive but simplified hillslope models. Each simulator presents one or more slopes described by a small set of variables, such as gradient, material strength, vegetation and hydrological state; mitigation and land - use choices modify these variables and thus the stability margin [69; 70]. The system responds with occurrence or absence of landslides and with indicators of damage severity. This preserves core causal relations between hydrological loading, strength and failure while keeping the decision problem manageable.

Feedback context is a deliberate design variable. In decontextualised modes, consequences appear as scores or abstract indicators, with little spatial information. In contextual modes, the same physical behaviour is embedded in simplified landscapes that show buildings, roads and people at risk; feedback includes visible damage to these elements after failures [69; 70]. Comparing these modes allows analysis of whether contextual, visually rich feedback produces more robust understanding than abstract feedback using the same hazard engine.

Limitations

To support controlled experiments, the landslide models compress real - world complexity. Slopes are schematic and homogeneous; interactions among multiple slopes, long runout distances and deep - seated failures are excluded [69; 70]. Triggering is based on simple rainfall or groundwater thresholds without explicit representation of temporal rainfall structure, antecedent moisture or complex geology. The tools therefore illustrate qualitative relations but are unsuitable for site - specific hazard assessment.

Stakeholder roles and institutional settings are narrow. Participants act as generic managers of protection budgets; there is no representation of infrastructure operators, emergency responders or households with distinct constraints. Zoning rules, warning systems and evacuation protocols are absent, which limits extrapolation to real governance contexts [69; 70].

Connections to critical infrastructure are implicit. Some scenarios reference buildings or roads as elements at risk, yet the simulators do not model network behaviour, redundancy or cascading failures. Infrastructure serves mainly as a damage indicator, not as a system with its own dynamics. For a review centred on critical infrastructure, these landslide tools mainly inform how individuals learn about slope risk and feedback, while infrastructure - focused landslide risk and asset management re-main under - represented.

4.3.3. Earthquake

Objective

Among the natural hazards affecting critical infrastructure, earthquakes are among the most extensively studied and simulated phenomena in education and professional training. Because of their capacity to trigger cascading effects, from structural collapse and fire outbreaks to service interruptions and socio-economic disruption, preparedness is essential for ensuring both system continuity and public safety.

With regard to the temporal dimension of seismic events, typically divided into foreshock, main shock, and aftershock stages, training applications primarily focus on the latter two 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 [53]. School - based programmes have repeatedly demonstrated that structured feedback and post - simulation reflection significantly improve understanding and knowledge retention among both students [18, 107, 112] and teachers [97] 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 [19, 42, 52, 111].

Together, these complementary objectives integrate cognitive, procedural, and emotional preparedness, forming the pedagogical foundation for multi - level learning environments that combine analytical rigour with experiential realism.

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 [19, 67] and immersive VR-SGs [42, 52, 53, 111, 112, 113] 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 [18, 97, 107, 112]. 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 [53, 112]. 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 programmes 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 [95, 111], while the multi-hazard system developed in [53] 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 operationalise institutional guidelines within participatory and educational settings, fostering consistent safety behaviours 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 se-lection and coordination under uncertainty [42]. In more advanced configurations, operators are immersed in virtual reconstructions of collapsed urban areas, performing triage and hazard recognition tasks [52]. 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 particularly significant example is represented by the VRRescue project, developed and tested within the Urban Search and Rescue Training Center of the Italian National Firefighters Corps located in Pisa [52]. The facility integrates a large-scale physical mock-up of collapsed structures with a virtual counterpart derived from photogrammetric 3D models of real post-earthquake environments. Professional rescuers use the simulation to practice victim localization, triage, and coordinated intervention, confronting realistic damage conditions that mirror those encountered during

operational missions. By combining virtual and physical modules, the Pisa initiative demonstrates how immersive technologies expand national training capacity, 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 [67].

At a more systemic and multi-hazard level, dynamic modelling frameworks capture the earthquake as a complex process capable of triggering secondary hazards such as fires, explosions, or landslides, and propagating effects across interdependent infra-structure networks [19]. 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 [54, 107, 113], schools [97, 112], and hospitals [95, 111], to urban neighborhoods and open public areas [19, 42, 52, 53, 67].

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 [18, 107, 112]. 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 [111].

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 [95]. 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 [95].

Beyond perceptual realism, simulation research increasingly focuses on the computational modeling of structural damage. In the Auckland City Hospital simulation [95], 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, achieving a realistic depiction of seismic effects without compromising performance. This approach reflects a broader methodological trend across VR earthquake simulations: dynamic behaviors are scripted procedurally, while static damage states are precomputed or visually 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-storey buildings. Analytical frameworks compute damage externally through quantitative models and import results as pre-processed data [19], whereas educational simulations often rely on simplified procedural logic sufficient for pedagogical realism [107, 111, 112].

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 [19]. Qualitative representations, typical of educational simulations [107, 111, 112], 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 modelling [53]. 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.

These varied approaches to perceptual and computational realism reveal both the technological maturity and the current constraints of earthquake-simulation research.

Limitations

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

- **Physical fidelity vs. interactivity.** Realistic ground motion and structural de-formation 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 [58; 57].
- **Validation and curricular integration.** Few studies measure long-term retention or validate VR performance against real emergency behaviour. Embedding immersive training into national curricula remains an ongoing challenge [97, 107, 112].

Despite these constraints, immersive earthquake simulations mark a decisive step in resilience education, bridging analytical rigor, experiential learning, and behavioral adaptation. By combining engineering precision with emotional realism, they strengthen preparedness across both public and professional domains.

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 [78; 79]. Immersive VR field trips reproduce access to remote or dangerous volcanic sites so that university students and researchers can practise mapping and measurement tasks in realistic outcrops without field travel [98]. A probabilistic event - tree model, BET_UNREST, targets scientific teams, seeking to familiarise them with structured probabilistic diagnosis of unrest and short - term eruption likelihood during crisis simulations [71].

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 [78]. The ARGEO mobile app delivers similar content on smartphones, with labelled 3D volcanoes, brief videos and embedded quizzes used as pre/post tests of understanding [79]. 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 [98]. 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 [71].

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 [78]. 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 [79]. 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 [98]. 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 [71].

Limitations

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 [78; 79]. The VR fieldwork system prioritises geometric realism but omits dynamic eruptive phenomena and provides limited systematic evidence on learning outcomes across student cohorts [98]. 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 [71]. Across these studies, infrastructural assets appear, if at all, as part of the surrounding landscape, and there is no explicit modelling of infrastructure performance or cascading effects under eruptions, which restricts direct application to critical - infrastructure - centred training.

4.3.5. Fire

Objective

Within the domain of critical infrastructure, fire constitutes a cross-cutting and recurrent hazard: a rapid combustion process that, through the release of heat, smoke, and toxic gases, can compromise the tenability of spaces and the operability of systems within minutes. In the context of training and education, fire must be addressed not only as an isolated emergency but as a systemic phenomenon affecting multiple interdependent infrastructures - energy, telecommunications, transport, and water, and therefore as a critical component of resilience education.

From a risk perspective, the literature consistently frames fire around three main vulnerability domains: (i) Operational continuity [22, 30, 46, 57, 77, 82, 93, 110, 126]; (ii) Occupant behavior and evacuation [20, 21, 23, 28, 47, 48, 57, 58, 65, 76, 82, 84, 85, 87, 91, 94, 102, 108, 115, 119, 121, 143]; (iii) Energy escalation [22, 24, 103, 116, 120].

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

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

Within the analyzed corpus, approximately thirty directly or predominantly address fire, focusing on training and simulation applications. Following a hazard-exposure-vulnerability-consequence perspective, events can be categorized by origin and operational domain, illustrating how ignition mechanisms, exposure conditions, and infrastructural settings jointly determine risk profiles and training priorities.

Natural or wide - area fires occur under adverse climatic and meteorological conditions or within all - hazards 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 [46, 47, 85].

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 [91].

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 [24, 93, 103].

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 [110, 120, 126], railway [82, 119], underground/tunnel [28, 57, 58, 108], and hydrocarbon supply chains [30, 77], 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 [84, 94, 115, 121], universities [23, 48, 87, 102], airports conceived as building systems, offices/civil and commercial buildings [20, 21], and training towers [65].

Collectively, the literature demonstrates that virtual fire-safety training applications cover a broad continuum, extending from individual awareness programs to complex operational simulations reproducing realistic multi-agent emergencies. On the non-immersive end are simulations and online (desktop-based) platforms

designed to illustrate evacuation plans and behavioral guidelines - focusing on route identification, exit recognition, awareness of hazard sources, and the proper handling of hazardous items/materials - primarily targeting occupants and visitors. Typically, low-cost and highly scalable solutions include web/virtual-world environments with assessments of knowledge, retention, and attention [48], desktop serious games for schools [84], and “hybrid” collaborative environments with a non-immersive option [47].

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 [57, 58, 76, 85, 94, 102, 103, 110, 115, 119, 120, 126]. 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 [21, 23, 24, 28, 30, 65, 82]. By contrast, studies on synchronous multi-role exercises and joint decision-making in complex scenarios via multi-user collaborative platforms remain limited [57, 58, 47, 126].

Representation of the phenomenon

The virtual representation of fire and smoke propagation follows a methodologically consolidated pipeline. Most mature studies 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 8: a, Fire model; b, Smoke model.

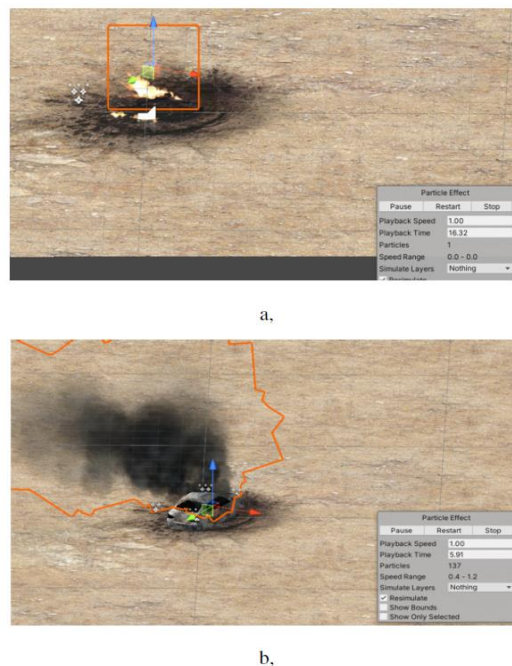


Figure 13: Representation of fire and smoke phenomena, adapted from Thach et al. [110]. © 2024 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

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 optimised for real-time performance [58]. 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 [94]. 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 [30, 110]. At the opposite end, desktop and web-based solutions remain more scalable but less behaviourally 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 path-finding logic [21];
- metaheuristics such as Particle Swarm Optimization (PSO) shorten evacuation time and path length [24];
- Deep Reinforcement Learning (DRL), combined with IoT sensors and Digital Twin (DT) data, enables adaptive guidance, re - routing occupants dynamically during evolving emergencies [23].

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 [21, 23, 24, 28, 30, 65, 82]. This integration supports data - rich, adaptive scenarios, extending the role of fire simulation from training to operational decision support.

Limitations

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 [58, 94].
- 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 [94].
- Collaborative synchronization. In multi-user contexts, latency, avatar embodiment, and limited spatial audio undermine teamwork and coordinated decision-making [57, 58].
- Validation and institutional integration. Few studies assess long-term retention or embed VR fire training in professional curricula, limiting adoption in formal education [115].

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 [58, 94,115].

Overall, fire simulations exemplify the integration of computational modelling, human-factor design, and immersive learning. By translating complex thermofluid phenomena into experiential scenarios, they advance both individual preparedness and systemic resilience across critical infrastructure domains.

4.3.6. NaTech, Technological, and Human-Induced Hazards

Objective

Natural Hazard Triggering Technological Disasters (NaTech), technological hazards, and human-induced hazards define a continuum between natural and anthropo-genic risk conditions in critical infrastructures. In practice, adverse events rarely originate from a single cause: they emerge from the interaction between natural triggers, intrinsic technological vulnerabilities, and human and organizational factors across tightly coupled systems. Within this continuum, NaTech events occur when earth-quakes, floods, storms or other environmental extremes initiate failures in engineered structures and processes; technological hazards arise from process instability, equipment ageing, or failures of supervision even in the absence of external shocks; human-induced hazards include both unintentional errors and violations, and intentional acts such as sabotage or terrorism that exploit existing vulnerabilities.

In this context, immersive simulation and extended reality (XR) systems are used to convert high-risk, low-frequency situations – often impossible or unacceptable to re-produce on site – into controlled learning experiences. Across open-pit mining, construction, process industries, transport systems and power infrastructures, virtual environments reconstruct work sequences, near-misses, equipment malfunctions and critical environmental conditions, exposing trainees to the consequences of their actions without exposing them to physical danger.

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.

Consequently, training aims to embed human-machine interaction and digital supervision within operational readiness: operators learn not only how to execute tasks, but how to interpret alarms, cooperate with automated systems and anticipate failure propagation across interdependent networks. In this sense, NaTech, technological and human-induced scenarios become a crucial component of resilience education, linking the engineering of protection and control systems with the behavioral and organizational competencies required to operate them safely in complex, evolving environments.

Applications

In high-technology systems, risk does not appear as an anomaly, but as an intrinsic possibility that emerges from the interaction among complex components, stringent procedures, and human limitations. In this context, XR applications for operational safety are primarily oriented toward training on complex operational and maintenance sequences and on the coordinated management of inspection, maneuver, and emergency response phases. Training systems for electrical safety [31, 89, 117] propose scenarios in which operators practise 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 [117]. In distribution networks and power generation, immersive platforms for substations and hydroelectric power plants [26, 64, 89] 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 [26, 30]. In the energy sector and process industry, immersive scenarios for the maintenance of marine engines and generator sets [104, 114, 122] and for safety training in oil and gas facilities [92] 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 [104].

In the construction and underground works sector, VR and VAR environments are used to anticipate high-risk site conditions, where the co-presence of machinery, spatial constraints, and rapidly evolving operational phases generates configurations that are difficult to control in situ. Safety training systems for open-pit quarries [59] and infra-structure excavations [33] 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 [83, 88]. 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 [49, 51, 68]. The theme of working at height and in emerging energy contexts is addressed through simulations of wind tower erection [50] and maintenance of photovoltaic systems [29], in which participants practice access procedures, use of 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 [60], 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 [32].

Another group of applications focuses on emergency management and techno-logical 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 [34, 86]. 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 [35]. 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 [30, 77]. 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 [64, 105]. 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 [22, 24, 103]. In the aero-nautical 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 [27, 90].

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 [75, 118]. 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 [32]. 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 [59, 106, 109, 117]. 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 [61].

Collectively, these applications converge toward a unified pedagogical space in which technological precision and behavioral realism are jointly cultivated. By combining procedural rigor, cognitive engagement, and emotional calibration, immersive simulations across the NaTech–technological–human-induced continuum transform complex emergencies into actionable training experiences that strengthen both system safety and human preparedness.

Representation of the Phenomenon

In the contributions included in this cluster, NaTech, technological and human-induced risks are represented through virtual environments that articulate the phenomenon along three intertwined levels: the spatial and infrastructural configuration, the evolution of technical–industrial processes, and the actions of human subjects 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 [30, 33, 34, 59, 89, 105]. 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 [75, 96]. 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 [33, 59] and for infrastructural and energy construction sites [29, 68]: 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 [29, 33, 59, 68]. 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 shut-downs [29, 59, 77]. 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 [33, 68, 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 [59, 86, 92, 114]. Users interact with the environment via controllers, pointers or gesture-based interfaces to inspect, select tools, confirm procedural steps and operate controls [27, 29, 33]. 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 [22, 31, 64, 117].

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 [30, 34, 77]. 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.

Limitations

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

- **Model coupling:** consistently integrating environmental triggers with industrial process models remains technically complex and data-intensive; in most studies, the natural hazard is treated as a simplified narrative background and attention is focused on downstream consequences, without fully representing the physical and organizational propagation chain of the event.
- **Emotional balance:** representing traumatic or violent events requires careful calibration in order to preserve psychological safety without reducing pedagogical depth; only a few contributions explicitly discuss criteria, guidelines, or metrics for tuning the intensity of audio-visual stimuli, the level of induced stress, and the differentiation of emotional load according to different user profiles.
- **Behavioral validation:** few studies verify the transfer of simulated reactions into real-world behavior or their retention over the long term; evaluation focuses predominantly on knowledge tests and immediate self-report measures, while robust longitudinal evidence is still lacking to link immersive training to observable changes in operational practices, near-miss indices, and accident rates.
- **Systemic integration:** multi-user coordination and the modelling of interdependencies across infrastructures remain limited, reducing the realism of cross-sector crisis simulations; the unit of analysis is often the single plant or department, and only rarely are impact chains that span multiple networks (energy, transport, communications, emergency services) explicitly simulated.

Considered together, these limitations delineate a state of the art in which immersive simulations describe hazardous conditions and individual behaviors effectively, but still struggle to fully represent the physical, temporal, and systemic complexity of the hazards that characterize contemporary critical infrastructures.

4.4. Critical Infrastructure domains

In the context of CI resilience, immersive and data - driven technologies are being increasingly deployed across diverse sectors, from energy and transport networks to healthcare systems and civil protection agencies. Each domain presents distinctive operational logics, spatial configurations, and vulnerabilities, yet the pedagogical objective remains constant: to develop systemic awareness and procedural competence in environments where safety, service continuity, and coordination must coexist.

Within these domains, simulation does not merely replicate physical spaces; it operationalises interdependence, between assets, processes, and human roles, turning infrastructures themselves into learning ecosystems.

Training applications frequently mirror the operational structure of CI systems, where interdependencies between assets, services, and actors determine overall performance during crises. In this perspective, simulation environments reproduce not only material configuration of infrastructures but also their socio - technical hierarchies, supporting coordinated learning across multiple organizational layers.

At the same time, several studies treat the urban built environment as a form of socio - technical infrastructure in its own right, the spatial framework that sustains community resilience and everyday functioning. Figure 15 summarizes the distribution of the reviewed studies across critical infrastructure domains, highlighting how training and simulation applications concentrate in a limited set of sectors while progressively expanding toward a wider range of socio-technical systems.

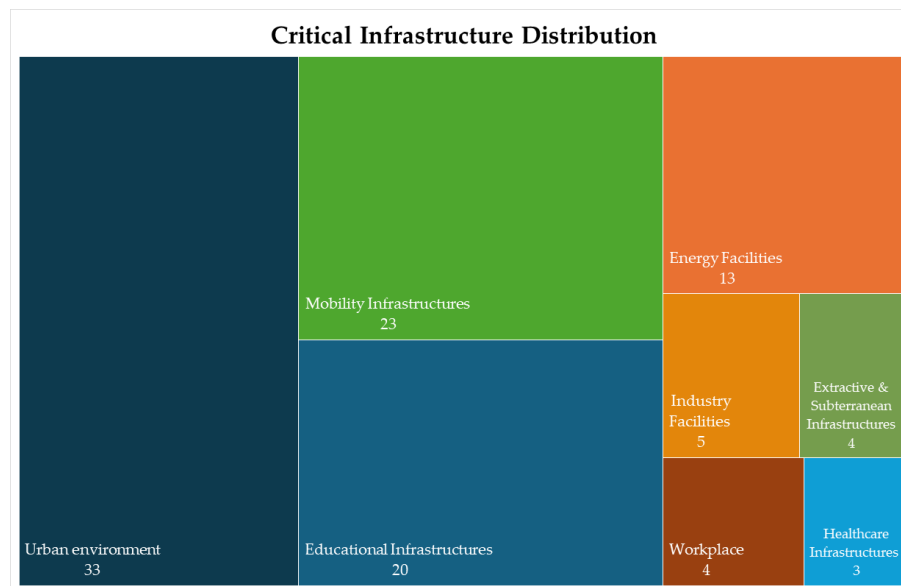


Figure 14: Critical Infrastructure distribution over selected papers. Image created by the authors.

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 both economic functionality and emergency accessibility. Their operational complexity stems from the intersection of confined geometries, high user density, and continuous interdependence with energy, communication, and safety networks. The geometric continuity of infrastructural elements (tracks, carriageways, tunnels) and the presence of nodes and specialised technical spaces (driver cabins, engine rooms, loading areas, construction sites) directly determine the level of exposure to risk. Within such 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. Rather than merely providing spatial description or visualisation, these systems operate as instruments for orchestrating interactions among heterogeneous actors (passengers, pedestrians, operators, emergency response teams, maintenance technicians) throughout the entire life cycle of the infrastructure, from design and construction phases 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 modelled as digital twins to train coordinated crisis response in confined, high-density environments. The EGCERSIS project [108] 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 [86], as well as in internal corridor segments characterized by constrained geometries, specialized equipment and strong dependence on signaling logics and centralized control [119]. At a broader scale, the digital-twin model for derailment scenarios presented by Xu et al. [34] 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 modelled together, enabling the planning and testing of recovery operations within a high - fidelity reconstruction of real line segments. Expanding this modelling approach to the train itself, the locomotive crew VR training system [35] 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 [61] 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.

In underground and tunnel infrastructures, the integration of BIM and VR allows for high - fidelity reconstructions of linear corridors, escape routes, and technical chambers. The BIM-VR model for emergency management in motorway tunnels [28] demonstrates how the layout of escape routes, SOS niches and installations, enriched by semantic metadata, is essential for constructing plausible and reusable scenarios, even though such assessments remain qualitative and limited to a single case study. Extending this approach, the FrèjusVR system [57, 58] exemplifies multi-user and multi-role learning: firefighters, truck drivers, and civilians act concurrently within the same digital replica of a road tunnel, practising alarm activation, communication, and decision - making. The resulting scenarios not only test procedural timing but also social coordination, showing that mutual visibility among avatars significantly enhances collective situational awareness and perceived realism.

At the urban scale, this perspective extends to metro systems, where the VirtualSafeConDM framework [68] 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 [77] highlight the specificity of roadside hazards and the need to train highly specialised

operators. VR applications for hazard recognition in motorway work zones [51, 88] reconstruct corridors and construction areas - as shown in Figure X - to systematise hazard identification and decision - making. The Immersive Cross - platform X3D system [49] 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 [96] 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 use of private vehicles during evacuations and the congestion it generates [72], or the management of hazardous - goods transport at the interface between industrial logistics and the public road network [77]. Across these cases, roads and tunnels are treated as infrastructures whose geometry, capacity and connectivity directly condition the feasibility of protective actions.

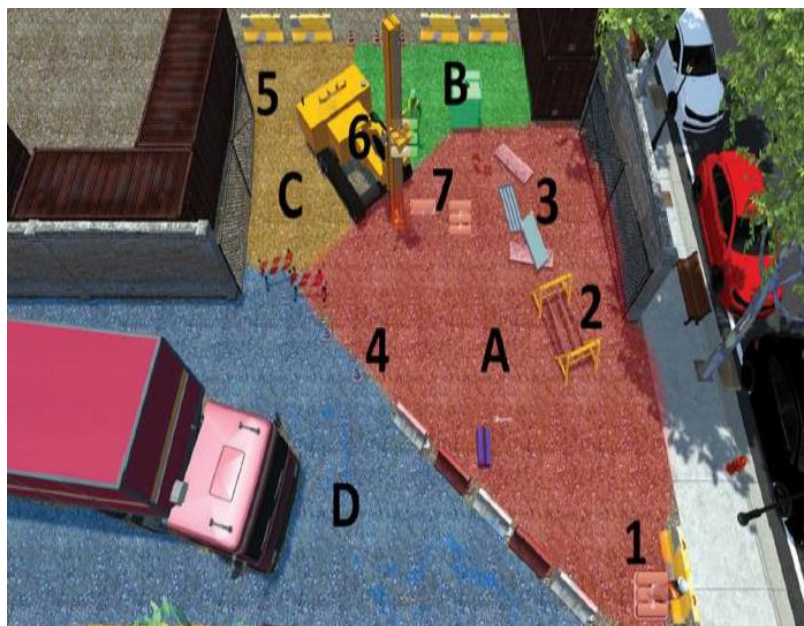


Figure 15: Work zone of the VR scenario. Reproduced from [88], © 2023 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0)

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 [90] and AR-based pre-flight inspection [27] show that simulated scenarios and digital overlays support procedural standardisation and situational awareness, strengthening adherence to safety protocols among flight crews and maintenance personnel.

Beyond land-based and airport systems, maritime transport infrastructures - which include ports, shipping routes and onboard technical spaces such as engine rooms - constitute an additional layer of the mobility network, in which navigation, propulsion and emergency management are tightly coupled within highly confined industrial interiors. In this domain, ship engine rooms emerge as critical industrial subsystems of the transport infrastructure, where propulsion units, auxiliary systems, piping networks and control panels are concentrated in compact, evacuation - critical and operationally dense spaces. In the training system described by Hamed-Ahmed et al. [126], the engine room and, in parallel, the galley are identified as areas with the highest incidence of fires: drill scenarios are structured according to different levels of severity and controllability, requiring trainees to locate the fire source, activate the procedures prescribed by SOLAS

(the International Convention for the Safety of Life at Sea - alarm, communication with the bridge) and decide between local extinction and evacuation along predefined escape routes. A further noteworthy example is the ShipSEVR project [122], in which the engine room of a platform supply vessel is modelled as a high-fidelity technical space, where generator sets and auxiliary systems are integrated with plant schematics and digital documentation accessible in VR, shifting the focus towards maintenance procedures and safety practices.

Complementarily, Thach et al. [110] develop a maritime VR training setup coupled with a shipboard fire-alarm hardware architecture, modelling container-ship spaces (e.g., engine room, electric room and bridge) in Unity and linking alarm panels/HMI monitoring to the virtual scenario to let trainees detect and localize fire events and re-hearse onboard response procedures. Other studies on electrical-safety training in the maritime domain [120] further extend this perspective to the high-voltage onboard electrical system, confirming that the ship's technical interiors - both mechanical and electrical - constitute essential nodes for the overall resilience of the maritime transport system. More generally, the experimental study by Makransky and Klingenberg [114] shows that, in maritime safety training (for example, dynamic risk assessment during mooring operations), VR simulators can outperform traditional instructor - led training in terms of motivation, perceived learning and intentions for behavioral change, high-lighting the potential of immersive solutions as a scalable tool for standardised and just - in - time training across global fleets. These contributions show that maritime transport requires immersive environments capable of simultaneously representing navigation constraints, technical interiors and emergency response strategies.

Taken together, mobility infrastructures provide a paradigmatic field for understanding how immersive learning can align human cognition with complex, networked systems. Across all transport modes, the evidence shows that virtual and mixed - reality environments transform linear, high - density infrastructures into shared cognitive spaces where procedural accuracy, communication, and adaptive reasoning can be rehearsed safely and iteratively.

4.4.2. Extractive and subterranean infrastructures

Extractive and subterranean infrastructures - encompassing underground mines and open - cast quarries - represent inherently critical environments, where the inter-action between unstable materials, mechanical operations, and constrained spaces produces a persistent state of risk. Activities near ignition sources, the handling of weak or fragmented rock masses, and the possible presence of toxic gases make fires, collapses, and reduced visibility recurrent hazards. What distinguishes these two contexts is their operational setting: underground mining unfolds within confined voids, ventilation networks, and limited egress routes, while open - cast extraction occurs in ex-posed environments characterised by excavation fronts, variable slopes, and the need for continuous control of stability and material handling.

Across the reviewed literature, two key principles emerge for workforce training in these domains: spatial continuity and operational coherence of the learning environment [93, 59].

The simulation developed for the marble quarries of the Apuan Alps [59] exemplifies these principles. It reconstructs a real site as a system of interconnected scenes linked by access ramps, where yards, quarry faces, and drilling areas are represented with realistic elevation data and populated with virtual machinery and operators. This configuration reproduces typical conditions of instability, manoeuvres in confined spaces, and human - machine interference, creating an immersive environment in which participants can rehearse coordination and safety protocols in context.

For underground mines, training for Australian rescue brigades adopts a whole - of - mine model that virtualises approximately 50 km of galleries and roadways, integrating fire and smoke - release scenarios along a continuous network of drifts [93]. This large - scale simulation reproduces not only geometry but also the sensory and operational complexity of emergency response underground - darkness, visibility gradients, heat, and noise - allowing teams to practise navigation, communication, and time - critical decision - making under realistic constraints.

This approach is further extended by Kaarlela et al. [105], who construct a high - fidelity virtual environment from a laser - scanned point cloud of mine cavities at depths of around 400 m. The resulting model, integrated into a Unity - based simulation framework, supports interactive training on emergency response to fires, explosions, haul - truck accidents, and co - worker injury. Workers engage directly with realistic

representations of equipment and spatial configurations, allowing the simultaneous training of procedural execution, spatial reasoning, and team coordination.

Taken together, these studies frame the mine as a continuous infrastructure of workspaces and access routes, where connectivity, atmospheric conditions and the presence of heavy equipment directly define manoeuvring margins, evacuation paths and intervention strategies.

Across these applications, quarries, mines, and related infrastructures such as trenches and drilling pads are treated as socio - technical systems, where excavation volumes, functional areas, and safety perimeters are modelled and manipulated in ex-tended reality to reproduce realistic gallery networks and open - pit morphologies. This approach supports navigation, hazard recognition, rescue training, and operational planning in both underground and open - air industrial contexts. The combination of accurate topography and contextual auditory feedback - wind, machinery, drilling, and cutting noises - strengthens situational awareness and procedural learning, demonstrating how XR can reproduce the perceptual and operational complexity of real ex-traction sites. In several studies, high - fidelity geometric reconstructions of tunnel and cavity networks [105] are coupled with process - simulation logics and robotic systems, transforming the mine into a testbed for digital - twin concepts and advanced automation. These hybrid environments anticipate, in embryonic form, many of the solutions that later appear in industrial and energy domains, where immersive technologies evolve from spatial training tools into integrated platforms for simulating complex plants, hazardous processes, and control infrastructures.



Figure 7. VR course on primary cutting upstream (SO1). Before starting horizontal cutting, the user interacts with the pointer, verifies the compliance of the operational phase checking the safety distances from the machine (a), positioning the diamond wire guards in order to avoid whiplash in the event of wire breakage during horizontal cutting (b). Source: authors' processing by Software Simulation version 1.2.1.

Figure 16: VR training for primary upstream cutting (SO1): safety-distance verification (a) and positioning of diamond wire guards before horizontal cutting (b). Reproduced from [59], © 2025 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0)

4.4.3. Energy facilities

Energy infrastructures represent a core subset of CI, where the continuous generation, conversion and transmission of power are closely linked to high technological hazards such as fire, explosion, release of hazardous substances and blackout. Within the corpus, this domain encompasses electrical power systems and substations, gas-fired power plants, onshore and offshore oil and gas (O&G) facilities, and renewable energy plants such as hydropower stations, wind towers and photo-voltaic farms. These systems range from relatively compact configurations, for instance gas power plants centred on a few generator sets within a single building, to highly distributed production chains that span extraction, processing, storage and transport across large territories. Despite their heterogeneity, these systems share a fundamental educational challenge: training operators to manage complex, high-risk environments where spatial configuration, process control, and emergency procedures are tightly interwoven. Immersive and data-driven applications operate here as safe surrogates for high-risk environments, enabling user to explore plant layouts, identify safe and unsafe paths, and rehearse emergency, maintenance and inspection procedures that would be too dangerous or costly to replicate on site.

The reviewed literature covers four main infrastructural configurations: electrical systems, gas power plants, Oil&Gas facilities and renewable energy installations, showing how VR, AR and XR - based simulators

couple spatial models, process logics and safety mechanisms to enhance preparedness, operational continuity, and systemic resilience.

Within the electrical power sector, immersive applications focus on substations, technical rooms, and work sites along live lines, where operations involve high-voltage components and sequential safety procedures. Substation simulators [89] reconstruct actual high/medium-voltage facilities in 3D, including bays, switching equipment and operator pathways, allowing trainees to rehearse opening and closing of circuit breakers, disconnectors and earthing switches while visualizing the consequences of incorrect sequences. Low-voltage training systems [117] further re-produce full operational workflows—from PPE selection and lock-out/tag-out procedures to voltage verification, helping learners internalize each step under realistic conditions. Studies comparing different feedback modes (visual, textual, auditory) show how multimodal cues can improve comprehension, reduce cognitive load, and sustain motivation [31]. VR - based education systems aim to strengthen engagement and adherence to safety practices by simulating electric shock and fall accidents during elevated component replacement, explicitly highlighting hazard points along the entire operational process [109]. Other platforms extend training to risk prevention and robotic assistance, for example using VR to test teleoperated interventions near energized equipment, showing how immersive environments can also support the design and validation of safety robotics [22].

In gas power plants (GPPs), the interaction of combustion, pressurized equipment, and confined environments introduces additional risks that require high procedural accuracy. Immersive simulations for GPPs [103, 104] reproduce complete sequences of maintenance and emergency management: participants identify leaks, execute shut-down procedures, and locate main gas valves under rapidly changing conditions, or perform routine maintenance operations – such as air filter replacement – in accordance with the plant's HSE requirements [104]. The simulation proposed by Kwegyir-Afful [103] exemplifies this logic, modelling a conceptual gas-engine facility where a leak triggers a fire and trainees must safely evacuate through the nearest exit and isolate the fuel supply. These scenarios demonstrate how immersive technologies allow repetitive, feedback-driven practice of critical actions while maintaining physical safety. By visualizing the relationship among process units, escape routes, and control devices, these systems reinforce spatial reasoning and adaptive behavior.

In the transition from natural GPPs to Oil & Gas (O&G) infrastructures, the focus shifts from relatively compact energy systems - centred on a few generation units housed within a single building - to much more distributed production chains that encompass hydrocarbon extraction, processing, storage and transport. Whereas in GPPs the risk profile is governed mainly by the fuel - combustion chamber - exhaust circuit and by the management of a confined high - energy volume, O&G infrastructures in-volve large inventories of flammable substances, extensive piping and tank networks, complex process units and a strong integration with logistical and transport systems. It is therefore not surprising that the study by Mujtaba Asad et al. [92] on Pakistani Oil & Gas industries shows that this sector remains among the industrial domains with the highest incidence of major accidents, while at the same time highlighting a still largely unmet need for VR - based solutions specifically dedicated to safety training. In the corpus devoted to the O&G sector, onshore configurations - land - based facilities such as depots, terminals and process units connected to transport networks - and offshore configurations - platforms and marine units for on - board extraction, processing and power generation - are treated jointly because they belong to the same infrastructural chain and share a common core of hazards and plant logics. Although they differ in operational context, accessibility and evacuation strategies, the infrastructural approach to the facility - based on processes of separation, compression, pumping and storage of flammable fluids, potentially explosive atmospheres, work at height and confined spaces - remains substantially analogous.

In these infrastructures, the risk profile is dominated by the presence of large volumes of flammable or explosive hydrocarbons, pressurised equipment, ATEX atmospheres, highly constrained access and egress routes, and a systemic dependence on standardised operating procedures and a consolidated HSE culture. Mujtaba Asad et al. [92] shows that, within this framework, VR - based vestibule training has the potential to reduce injuries and fatalities, but must contend with economic and infrastructural barriers, as well as organisational resistance to the adoption of new technologies.

In onshore contexts, the oil depot system [30] reconstructs the site as a high - risk node - comprising tank farm, loading areas, piping networks and fire - fighting equipment - and employs separate inspection and

emergency modules to let users explore infrastructural anomalies and fire/explosion scenarios along predefined routes and operational roles.

Offshore, by contrast, study [26] models the platform power system as an isolated micro - energy infrastructure, virtualising the onboard substation and electrical equipment at real scale within a structured training environment, where switching sequences, fault conditions and operating states are controlled via programmable logic controller (PLCs). In both cases, VR makes the relationship between plant layout, risk - control devices and intervention procedures explicit; however, the depot application emphasises the spatial and collaborative dimensions of emergency response, whereas the platform scenario privileges the depth of modelling of power systems and plant behaviour.

Complementing these plant - and system - level perspectives, some contributions focus on the upstream and logistics segments of oil and gas infrastructures through analytical and extended - reality approaches. Machine - learning pipelines calibrated on core - flooding experiments are used to derive parameter distributions for enhanced - recovery models, supporting scenario analysis for reservoir development and production planning within the broader energy infrastructure [44]. Mixed - reality scenarios for accidents involving road tankers carrying dangerous goods, in turn, train crisis managers and emergency responders at the point where industrial supply chains intersect with public transport corridors [77]. Together, these works emphasise that oil and gas infrastructures extend from the reservoir to the roadway, and that both high - fidelity simulation and interactive training have a role in supporting their safe operation.

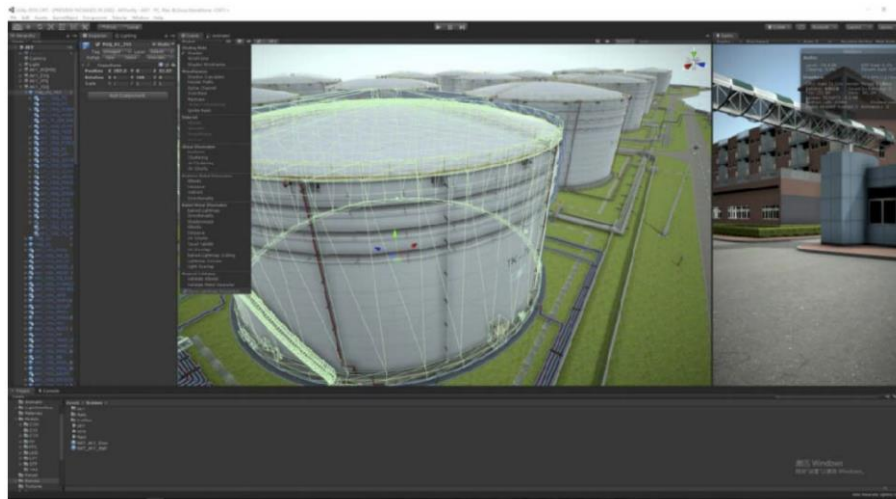


Figure 1. System development interface

Figure 17: System development interface of Oil and Gas plant. Reproduced from [30], © 2019 The Author(s), distributed under the Creative Commons Attribution License (CC BY 3.0)

Within renewable-energy subdomains, energy infrastructures are conceived as distributed systems strongly dependent on environmental conditions and characterized by hybrid risk profiles: electrical and mechanical hazards typical of generation facilities coexist with work-at-height exposure, difficult access, and variable weather. Hydro-power-plant simulations, such as Righi et al. [64], reconstruct a 132 MW reference facility with machine halls, control rooms, and access routes linked to hundreds of operational commands, enabling the training of multiple resilience skills—from decision-making and coordination to management of operational constraints under grid disturbances. From an infrastructural perspective, the plant is treated as a continuous socio-technical system in which the interaction between physical layout, supervisory systems and power-grid constraints are simulated in an integrated way to assess operators' ability to maintain performance under abnormal conditions.

Wind-tower simulators (Li et al. [50]) model vertical infrastructures with high fall and structural-collapse risk, guiding users through the sequential assembly process and emphasizing hazard recognition during each phase. Conversely, photovoltaic systems [29] interpret installations as diffuse infrastructures where electrical, fire, and height risks converge. In this case, based on field analyses, VR/AR gamified scenarios are designed for workers engaged in the installation, maintenance, and cleaning of photovoltaic (PV) systems. The virtual environment reproduces façades equipped with photovoltaic panels, manlifts, lifelines, and anchor points, structuring the workflow into four stages: PPE selection, preparation, work at height,

and closure, with predefined performance thresholds and simulated incident outcomes triggered by repeated errors.

Taken together, these examples illustrate how immersive and data-driven technologies serve as experiential laboratories for energy-sector training. By virtualizing substations, engine halls, tank farms, offshore platforms, machine halls, wind towers, and PV fields, XR simulators render the relationship between plant configuration, process logic, and protection systems both navigable and measurable. They enable operators and trainees to observe, interpret, and act within realistic yet controlled environments, improving procedural accuracy and cognitive readiness. At a systemic level, these environments pave the way for tighter coupling between training platforms, digital twins, and real-time operational data, linking safety education, predictive maintenance, and resilience management into a unified framework.

4.4.4. Industry Facilities

Industrial infrastructures constitute a core component of Critical Infrastructures, in which production lines, process units, research laboratories and control systems are organised in configurations characterised by high plant density and strong functional interdependence. In these environments, the risk profile is dominated by the presence of hazardous substances, pressurised equipment, moving machinery and operations in confined spaces, as well as by a high degree of automation and dependence on standardised operating procedures. In the analysed corpus, this domain includes both manufacturing and process facilities (e.g. assembly lines, production departments, construction sites and proto-plant configurations) and chemical and research laboratories, which operate as modular micro-plants with high variability in equipment and sub-stances. In both cases, immersive applications are used to make explicit the spatial structure of work environments, the sequence of operations and critical interaction points between people, equipment and safety systems, thereby enabling operators to be trained in hazard recognition, procedure implementation and incident management within highly complex techno-organisational contexts. This factory-centred perspective is reflected in the VR occupational health and safety training system by Lacko [106], which targets employees of industrial companies and reproduces both production and non-production areas through scenarios drawn from the normal operating practice of the factory, including stair circulation, warehouse logistics with racks and forklift traffic, and safe interaction with industrial machinery and equipment.

On the side of production facilities, the IVR platform for confined-space safety developed by Evangelista et al. [60] treats tanks, vessels, silos, manholes and under-ground chambers as critical sub - infrastructures within the plant. The virtual environment reconstructs enclosed volumes with limited access points, pipe connections and level differences, embedding step - by - step operational procedures for entry and work in confined spaces. From this perspective, the confined space is not only a training scenario but a node of the plant network, in which geometric configuration, atmospheric conditions and the presence of equipment jointly define error margins, safe routes and mitigation strategies.

In the case of chemical laboratories, both studies treat the laboratory as a micro process infrastructure, but with different emphases. In the training system for laboratory inspection [75], the environment is decomposed into 15 scenes connected by door tags, ranging from the entrance to the personal protective equipment (PPE) dressing area, from the workbench to the fume hood and the storage area: the laboratory is thus modelled as a sequence of functional spaces traversed by the inspector, in which safety and security hazards are “planted” along the path and made explicit through interactive hotspots. In the VR serious game for laboratory safety [118], by contrast, the company’s chemical laboratory is represented as a single operational environment in which benches, equipment and protection devices form the backdrop for tasks of risk identification, risk minimisation and safe execution of experiments. From a comparative standpoint, [75] emphasises the laboratory as an inspection infrastructure, articulated into nodes and links to be traversed systematically, whereas [118] conceives it as an immersive work infrastructure, in which layout and equipment primarily serve to contextualise player actions and to link operational choices, errors and consequences within a single experimental space.

Beyond worker-focused modules, industrial plants also appear as complex incident settings for operational response training: Wu and Liu [24] propose a 3D simulation-based fire-rescue training system that combines rescue path planning and risk assessment, and evaluates performance across scenarios including factory fires and chemical-plant fires (alongside other complex built environments).

Taken together, these industrial applications show how XR technologies are used less to reproduce large territorial networks than to expose and manipulate the fine - grained coupling between spatial layouts, equipment configurations and safety procedures in dense technical environments, complementing the large-scale, systems-oriented focus observed in the energy domain.

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. 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.

Beyond their technical function, these infrastructures illustrate a new dimension of resilience: informational resilience, 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.

4.4.6. Healthcare Infrastructures

Healthcare facilities represent one of the most intricate and interdependent categories of critical infrastructure, where spatial configuration, service continuity, and operational interconnection directly influence system performance during emergencies. The case of Auckland City Hospital (ACH), the New Zealand's largest public hospital and clinical research facility [95, 111], illustrates these dynamics particularly well, serving as a paradigmatic example of how large-scale healthcare systems behave under seismic stress. Selected for its operational complexity, high occupant density, and the essential nature of its functions, the hospital provides an ideal testbed for immersive training technologies aimed at operational resilience and emergency management. The facility consists of a multi-building complex that integrates clinical wards, diagnostic and surgical units, administrative offices, and public areas such as corridors, lobbies, and waiting rooms. These spaces are connected through a dense network of vertical and horizontal circulation routes, forming overlapping zones of access, movement, and responsibility. Within this intricate layout, staff, patients, and visitors share partially intersecting pathways, revealing the dual identity of hospitals as both care environments and logistical systems, where controlled circulation and open accessibility must constantly coexist. From an infrastructural perspective, ACH demonstrates how functional dependencies, for instance, between emergency exits, lift systems, and intensive care units, become critical under disruptive conditions. Its compact morphology and high occupancy increase the facility's exposure to non-structural damage, while its complex internal connectivity influences both the propagation of risk and the efficiency of evacuation strategies. As a simulated environment, Auckland City Hospital thus represents an invaluable spatial and organizational model for analyzing the resilience of healthcare infrastructures, highlighting how architectural form and functional inter-dependence shape performance during seismic and multi - hazard events. Complementarily, the study in [46] shifts the focus to a rural healthcare system, modelling it parametrically as an acute-care rural hospital (e.g., number of physicians and nurses, triage rooms, ER beds, and inpatient wards), while also integrating public-health and emergency-management subsystems; in this case, the main response variable is the overall performance of the healthcare/hospital system. Moreover, the adopted approach underscores the potential of VR for interdisciplinary training, integrating medical, technical, and administrative perspectives within the same virtual ecosystem.

Healthcare infrastructures exemplify how immersive technologies can bridge technical, organizational, and human factors, transforming complex service networks into living laboratories of resilience. Their methodological insights, on interdependence, redundancy, and coordinated evacuation, resonate across other infrastructural domains, from communication to education and urban system.

4.4.7. Workplace and office environments

In office environments, immersive technologies are increasingly used to reconcile operational continuity and safety training, turning the workplace into a laboratory for organizational and behavioral resilience. In this context, office environments represent a distinct yet increasingly relevant subset of critical and organizational infrastructures. Though less exposed to physical hazards than industrial or transport systems, offices concentrate human presence, digital assets, and service continuity dependencies that make them critical for institutional and corporate resilience. Immersive and simulation-based applications in this domain address primarily evacuation dynamics, behavioral adaptation, and cognitive responses to emergency cues. Several studies reproduce multi-floor office layouts and dense occupancy conditions to evaluate route selection, decision-making under alarm, and adherence to safety instructions, highlighting how cognitive load and spatial familiarity affect evacuation performance. Scenarios typically include fire, smoke propagation, and earthquake evacuation [54, 107, 113], focusing on spatial perception, stress management, and the communication of real-time alerts. More recent work deploys optical see-through AR systems directly in office corridors and circulation spaces to train building occupants in key fire-safety tasks and compares the effectiveness of this training with conventional video-based methods [110].

Beyond physical evacuation, some works expand toward organizational resilience and human-factor assessment, linking safety training with workplace well-being, ergonomic design, and psychological readiness.

4.4.8. Educational infrastructures

Educational facilities – in particular schools and universities – constitute a distinct class of critical infrastructure where safety management and knowledge dissemination converge.

Across the literature, AR and mobile-AR tools overlay geological or meteorological content onto textbooks, classroom walls or outdoor areas [78; 79; 43; 45; 80], turning ordinary lessons into situated explorations of risk while retaining the school building as a fixed spatial frame [78; 79; 43; 45; 80]. Other studies use school layouts, timetables and assembly areas as the backbone of evacuation drills and preparedness modules, pairing physical exercises or metaverse sessions with simulation outputs to help students and staff understand circulation patterns, bottlenecks and waiting zones [123; 72].

In educational settings, studies converge on the idea of using immersive environments to turn schools and campuses into true laboratories for emergency preparedness, while still adopting different technological and pedagogical approaches.

In public schools and primary education, virtual reality serious games reproduce typical school layouts and codified fire regulations, training pupils and teachers in evacuation procedures and emergency management through narratively structured scenarios [84, 94]. At university level, virtual replicas of teaching and laboratory buildings – including campus-scale virtual worlds and metaverse-based evacuation systems – allow the repetition of fire drills and the testing of dynamic guidance strategies under realistic occupancy conditions [23, 48, 87]. More infrastructural approaches combine digital twins of training towers and classroom blocks, multi-user preparedness platforms and VR games integrated into learning-management systems, engaging students, teachers and safety professionals in shared preparedness scenarios that can be monitored and adapted over time [65, 115, 116, 121].

These experiences demonstrate how schools can function as learning-critical infrastructures, spaces where architectural design, organizational routines and educational objectives align to promote a culture of preparedness. Evidence from controlled studies further indicates that VR-based fire safety programmes can strengthen knowledge of safety measures and individual awareness among students and academic staff, supporting the long-term internalization of emergency procedures [102]. Immersive technologies extend this paradigm, turning the very act of learning into a resilience-building process that links personal awareness, institutional readiness and community safety.

4.4.9. Urban environment

Urban and territorial infrastructures occupy a central position in resilience strategies, as cities concentrate critical assets, services, and populations within interdependent systems of transport, housing, and lifelines.

Overall, the case studies reviewed delineate a continuum of urban configurations and roles: from synthetic and regional city models developed for seismic and multi-hazard scenarios [18, 19, 42, 52, 53, 67], to representations of coasts, river corridors and neighbourhoods exposed to hydro-meteorological and coastal events [99, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96], up to XR frameworks and collaborative virtual reality environments that stage floods, compound disasters and large metropolitan emergencies [47, 56, 66, 91], while at a more local scale serious games and training systems focus the interventions of emergency services on urban buildings and public spaces [20, 21, 82, 85] and on infrastructure construction sites [33, 83].

Several studies, particularly those addressing seismic applications [18, 19, 42, 52, 53, 67], explore how immersive and simulation-based environments can represent, analyse and teach the interconnections between built form, hazard dynamics and human behaviour under emergency conditions. These contributions highlight the role of spatial, organisational and social factors in shaping collective response and recovery.

Early contributions, such as Zhou et al [67], operate at a regional scale, generating virtual cities composed of administrative areas, industrial districts, residential zones, and lifeline systems, including hospitals, schools, and emergency shelters. These synthetic environments are designed to train public officials in decision-making and inter-agency coordination, simulating large-scale earthquakes and their cascading effects on critical infrastructures. Building on this framework, [19] (Tian et al., 2018) refines the model into a parametric three-dimensional city, combining topography, vegetation, and street furniture to create a flexible and photorealistic environment. The system allows users to modify morphological and environmental parameters dynamically, tailoring simulation scenarios to specific local conditions and enabling cross-scenario comparisons for planning and response strategies.

Later immersive applications, such as VRescuer [42] and VRescue [52], shift the focus to collapsed and damaged cityscapes, enabling participants to navigate debris-filled streets and ruined structures during post-earthquake operations. In VRescue [52], Carrozzino et al. reconstruct a historic Italian city center through high-resolution photogrammetry and Unity-based physics simulation.

A complementary perspective is offered by De Fino et al. [53], who reintroduce open urban space as a key component of emergency management, focusing on public squares as social and logistical nodes during crises and employing Built Environment Typologies (BETs) to represent characteristic configurations of Italian urban morphology. By parameterising architectural form, spatial configuration and functional characteristics, BETs provide a structured and replicable framework for simulating multi-hazard conditions in typified public spaces and, in the prototype developed within the BE S2ECURE project, help to redefine these spaces not as simple static civic amenities but as functional components of the city's resilience infrastructure. Compared to indoor environments, outdoor spaces – whether used as primary training scenarios or as safe assembly areas at the end of indoor drills – are generally more simplified and schematic, due to their spatial complexity and scale [53], yet this abstraction is anchored in taxonomic assessments of real-world cases, which ensure a balance between realism and manageability. Through BETs [144, 145], public spaces thus become parametric learning environments in which urban form and emergency function are aligned within the same educational framework.

In parallel with seismic applications, numerous contributions broaden this perspective to include other hazards, particularly hydro-meteorological and coastal events, framing the urban environment as an interconnected system of streets, blocks, open spaces and key sites that must remain functional under different stresses [14, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96]. VR, desktop and XR tools that represent coastal towns, river corridors and slope-side settlements use building clusters, road hierarchies and critical nodes such as squares or bridges as the main objects of exploration, encouraging learners to reason about accessibility, exposure and continuity of essential services at the neighbourhood scale [99, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96].

Within this framework, the literature documents several cases in which specific existing urban contexts are modelled as immersive multi-hazard training scenarios. The historic centre and river corridor of Senigallia [56] are used to construct an extended reality framework that combines reusable typological scenarios and site-specific environments, with the aim of training citizens, technicians and decision-makers in flood-risk management and related civil protection measures. Within a multidisciplinary “dual hackathon” [66], the same type of flood-affected territory is employed as a testbed for coordinating engineering expertise, risk communication and operational decisions during a joint exercise involving universities and local authorities. A similar approach underpins the experiential training system MisasTer [91], which places participants in a coastal city subject to a sequence of earthquake, tsunami and fire, drawing on the official disaster-prevention map to structure realistic evacuation routes and assess the correct use of escape paths. At an even larger scale, the collaborative Megacity environment [47] represents a complex metropolitan area in virtual reality, in which multi-user teams can explore different crisis scenarios, test alternative strategies and observe how choices affecting individual assets ripple through interdependent infra-structure networks.

Participatory simulations further extend this vision at the urban scale, allowing groups of residents, students or decision-makers to modify measures such as local protection works, land-use options or emergency routes and to observe how these changes propagate through the urban fabric [124, 39, 125]. In these implementations, the urban environment is treated as a multi-level critical infrastructure in which built form, circulation and institutional decisions jointly determine resilience.

At an intermediate scale between the neighborhood and the individual public space, several serious games and training systems take the urban building and its immediate surroundings as the operational unit, alternating the perspective of emergency services with that of occupants. The serious game Fireman Rescue [85] places the player in the role of a firefighter responding to everyday urban scenarios – a burning waste container, a vehicle fire, a dwelling with victims to evacuate – and assesses the ability to follow operational protocols, select access routes and correctly use equipment and protective devices under pressure. Complementarily, the VR-based training system [20] proposes indoor scenarios set in typically urban facilities such as shopping centers and hospitals, highlighting how the distributive complexity of corridors, atria, wards and retail areas affects evacuation times and modes and fire-attack strategies.

On the side of occupants and egress management, the training model [21] 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 [82] 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.

In the same urban environment, several serious games and training modules bring flood- and water-protection systems to the foreground as infrastructures in their own right. VR and desktop scenarios model levees, mobile barriers, pumps, temporary protection units and drainage elements as manipulable components, asking learners to design or deploy configurations that protect streets, buildings and key functions under resource and time constraints [101, 73]. Data-driven and digital-twin platforms link hydrological behavior at catchment scale with local assets such as embankments, channels or sensor-equipped sites, making it possible to visualize how interventions on individual structures transform conditions at neighborhood scale [25]. In this perspective, protection systems are no longer passive background elements, but critical infrastructures that mediate the relationship between urban form and external stressors.

Finally, although they do not directly address the neighborhood scale, VR applications dedicated to safety in excavations [33] and in geotechnical drilling works [83] draw attention to an often overlooked dimension of the urban environment: that of construction sites and infrastructures under construction, where trenches, underground utilities and machinery in turn become critical risk nodes and must be considered within the broader framework of built-environment resilience. Complementarily, some VR-based safety-training studies address cross-cutting high-risk tasks such as con-fined-space entry, comparing a productive-failure instructional design with a directive-instruction approach to develop declarative knowledge on the selection

of safety equipment, within a confined-space scenario modelled on an actual sewage-dredging work site [32].

Taken together, these contributions present the urban built environment as a dynamic ecosystem in which digital modelling, immersive simulation and resilience pedagogy converge to foster systemic understanding. Whether addressing seismic or hydrological risks, these environments enable professionals, students and citizens to experiment with spatial configurations, cascading hazards and collective decision-making processes under stress. By integrating the logics of interdependence, adaptability and co-production within urban training frameworks, immersive simulations turn the city into a pedagogical instrument capable of cultivating the situational awareness and collaborative intelligence required by contemporary resilience governance.

4.5. Actors and stakeholders

The segmentation of stakeholders across the reviewed contributions reflects the growing ambition to make education technologies a cross-cutting formative approach, capable of engaging participants at different levels of competence, responsibility, and operational risk.

Within the analyzed literature, two main design logics can be observed. As shown in Figure 19, the reviewed corpus spans multiple actor categories, with Technical Workers and Process Operators emerging as the most represented group (35%), further detailed into Process and Plant Operators (13%), Field technicians and specialist workers (12%), and Technical Operators in Transport Systems (10%).

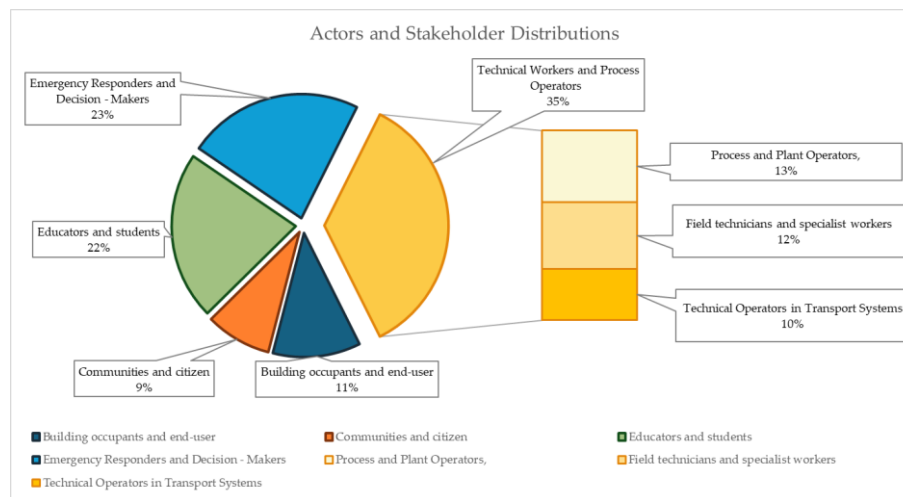


Figure 18: Actors and stakeholder distributions across the reviewed studies, including a detailed breakdown of the Technical Workers and Process Operators cluster. Image created by the authors.

Some studies start from the critical infrastructure itself [95, 107, 111], identifying the various categories of occupants and functional roles within it, such as operators, visitors, maintenance staff, and process managers. Others develop experiences tailored to specific user typologies [18, 52, 42, 54, 97, 112, 113], including rescuers, technical workers, or students. This dual perspective highlights how immersive technology support the mapping of human complexity within infrastructural systems, enabling an educational continuum that spans from the asset management workforce to the individual citizen. Within the hazard-focused subset, this dual logic reappears with different emphases. A large group of applications places school and university learners at the centre, embedding geohazards and hydrological risks into curricular activities or laboratory - style tasks [25, 36, 37, 40, 41, 43, 45, 73, 78, 79, 80, 99, 100, 123]. Others design participatory simulations and training frameworks that bring together residents, teachers, scientists, civil protection officers, and emergency responders in shared flood, landslide, tsunamis, or

hurricane scenarios, so that evacuees, planners, and crisis managers act in the same digital environment from distinct role perspectives [25, 38, 39, 56, 66, 69, 70, 71, 72, 74, 121, 124, 125]. These contributions extend stakeholder mapping beyond single institutions and tie education technologies explicitly 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 [57].

4.5.1. Emergency Responders and Decision-Makers

In the domain of crisis and emergency management [108], immersive simulations address a wide spectrum of professional profiles, ranging from operational responders in the field to institutional and strategic decision-makers. Together, these groups represent the backbone of emergency preparedness: one responsible for tactical execution under stress, the other for coordination and decision-making across organizational levels.

At the operational level, *VRRescue* [52] was specifically developed for Urban Search and Rescue (USAR) teams, enabling them to practice tactical and procedural decision-making in photorealistic post-disaster environments. These simulations combine physical realism and behavioral assessment, requiring participants to perform tasks such as navigation through debris, triage of victims, and use of professional equipment (GPS, dosimeters, radios). Beyond USAR-specific tools, several VR-based firefighting systems adopt similar logics for building and urban emergencies. A BIM-based virtual training environment [82] links information models of complex facilities such as airports and stations with simulated fires, smoke and explosions, so that fire crews can rehearse rapid orientation, team coordination and equipment handling in high-risk buildings. A multi-scenario training system [20] exposes participants to four typical fire contexts – shopping mall, hospital, dwelling and entertainment venue – where they must move through smoke, operate extinguishers, hydrants and fire doors, and manage lifts and escape routes. The serious game *Fireman Rescue* [85], designed for firefighter education, similarly places trainees in everyday urban emergency situations while recording actions, errors and timings to support debriefing and targeted feedback. Through iterative practice, trainees improve coordination, reaction time, and situational awareness, developing cognitive flexibility under stress.

Similarly, multi-role simulations like *FrèjusVR* [57, 58] involve distinct participant roles (firefighters, civilians, and truck drivers, who must collaborate, maintain safe distances) or trigger emergency procedures, linking individual behavior to collective safety. In parallel, the *HCP-VR system* [55] addresses hydrogeological emergencies, enabling Civil Protection responders to rehearse high-capacity pumping operations in flooded environments through guided and evaluated modes that integrate procedural instruction, safety protocols, and performance assessment. Within the same trajectory, the *EGCERSIS* platform [108] extends this logic to coordinated multi-actor response in transport environments, using a metro-station digital twin where firefighters, police, and medical teams operate under a shared decision-support system to rehearse complex emergency management workflows. A similar integration of sensing, monitoring and virtual environments is pursued by the *GUIDE2FR platform* [65], which couples a digital twin of a firefighter training tower and nearby buildings with robust wireless beacons, cloud-based data management and predictive air-quality models to support first responders and control-room operators during emergency exercises.

At the strategic level, a web-based tabletop system was developed to support decision-makers in managing command structures, inter-agency communication, and resource allocation during large-scale seismic events [67]. The environment reproduces hierarchical coordination, information exchange, and policy formulation processes, fostering collaborative reasoning and evidence-based decision-making. In a different sector, a proof-of-concept multi-method computer simulation for rural healthcare disaster preparedness [46] combines system-dynamics and discrete-event modelling to represent patient flows, capacities and triage processes, allowing health planners and emergency managers to evaluate how alternative preparedness policies and resource configurations affect service performance under catastrophic scenarios.

Among the most advanced implementations, the *VRRescue* training system, tested at the USAR Center in Pisa [52], exemplifies how immersive simulations are now being incorporated into institutional firefighter-

training programs. Similarly, *Fireman Rescue* [85] and *GUIDE2FR* [65] are now embedded in stable training facilities and programmes for fire brigades and civil protection services. Overall, these initiatives highlight the shift from experimental prototypes to permanent training infrastructures and signal the progressive integration of virtual reality and digital-twin technologies into official emergency-preparedness curricula.

Within the hazard - focused corpus, several systems target responders and crisis managers in transport and territorial settings. *Tunnel VR* training integrates BIM-based incidents so trainees practice lane closures, traffic control, and occupant guidance under fire and smoke [28], while mixed - reality ADR tanker scenarios use HoloLens overlays to rehearse stabilization, hazard identification, and first aid with logged procedural performance [77]. *HurricaneLog* captures how humanitarian logisticians and emergency managers plan stocks, shelters, and fleets under hurricane uncertainty [74], and *Flood Action VR* stages multi - phase flood missions for emergency services and volunteers, assessed mainly through usability and perceived preparedness [38].

At the institutional level, volcanic - unrest exercises convene scientists and civil protection officials around probabilistic BET_UNREST outputs [71], participatory flood simulations engage municipal staff and elected representatives on urban and coastal prevention portfolios [124; 39; 125], and tsunami evacuation planning links inundation models with school drills so teachers and local authorities jointly revise routes and assembly points [72]. XR frameworks extend this logic conceptually to multi - profile urban risk training, though implemented pilots remain limited [56].

Furthermore, across multi - environment settings, the use of VR reveals communication bottlenecks between control rooms and field operators, detects stress even among experienced personnel, and shows improvements in response times after just a few iterations. In parallel, data - driven solutions such as PSO - assisted routing and dynamic risk assessment support responders in complex scenarios, such as high - rise buildings or industrial plants, increasing efficiency and safety during fires and chemical releases [24]. To make this qualitative leap in training sustainable, and to close the gap between what is learned and what is done for these stakeholders, the evidence must be strengthened through longitudinal evaluations of real - world performance, outcome metrics beyond usability, and simulators designed to be age - inclusive and team - aware.

Taken together, these applications bridge the operational and institutional dimensions of emergency management, aligning tactical execution and strategic coordination within a shared digital ecosystem.

4.5.2. Technical Workers and Process Operators

Technical workers and process operators constitute the operational backbone of many critical infrastructures, particularly in industrial, energy, transport and protection systems. Within the reviewed corpus, these profiles can be interpreted through three recurring operational groupings: (i) process and plant operators, including plant and maintenance technicians, substation controllers, and – within the maritime domain – engine-room personnel, responsible for running and maintaining process assets and safety-critical equipment; (ii) field technicians and specialist workers, such as field operators and movable flood-barrier operators, who perform mobile tasks at the interface between infrastructure and its surrounding environment; and (iii) technical operators in transport systems, including locomotive crews and other railway technical staff, as well as tunnel controllers, who manage procedures and coordination in moving or spatially constrained contexts. Across all three groupings, daily activities directly mediate between complex socio-technical systems and material processes, meaning that errors may rapidly escalate into major incidents and that routine tasks are frequently carried out under tight temporal, procedural, and safety constraints, as well as under high levels of operational stress. Besides routine operations, several applications explicitly target emergency readiness through drill-like modules that rehearse recognition, response sequencing and evacuation under time pressure [102, 115], including multi-hazard drill logics where earthquake dynamics cascade into subsequent threats that must be managed within a single training flow [91].

Within the analyzed corpus, immersive training is employed to make explicit the coupling between spatial configuration, process logics and standard operating procedures, enabling these workers to rehearse

complex workflows, hazard scenarios and coordination patterns in controlled yet realistic environments. The main objectives are to improve procedural accuracy and safety performance, to strengthen operational coordination with co-workers, control rooms and emergency teams, and to develop skills for managing stress under abnormal or emergency conditions. In parallel, some contributions incorporate data layers and performance metrics (e.g., timing, errors, and behavioral indicators) to support scenario analytics and after-action review, thereby bridging procedural rehearsal with decision-support and preparedness evaluation [56, 121, 108].

In industrial and energy-related infrastructures, VR is widely used to support complex task training along the process chain. Evidence from the oil and gas and industrial-production domains [26, 30, 92, 106] shows that immersive environments are deployed for plant inspection and anomaly detection, commissioning and calibration tasks, emergency routines, and other high-consequence operations, reducing exposure to real hazards while minimizing costly operational errors and unsafe acts. Maintenance safety training is also reported through VR modules for plant maintenance procedures [88]. Comparable procedure-centric logics are reported for power-supply operations, where immersive modules train switching and testing routines for electric-power operation employees [31] and support periodic training for substation service personnel and on-duty operators [89], including offshore or high-risk configurations where procedural compliance and safety awareness are critical [26]. In parallel, targeted implementations focus on isolation and lockout sequences for low-voltage systems among operators, electrical specialists and operational HSE roles across industrial and utility settings [117], while emergency-oriented simulators extend training to the coordinated rescue actions of electric power field operators during incidents in distribution environments [22]. A closely related strand addresses safety training in automated production facilities, where VR makes interlocks, exclusion zones and stop conditions observable and testable, improving operator readiness when working near robots or semi-autonomous equipment [105]. Comparable emergency-preparedness patterns are also reported for underground and constrained industrial settings, where rare but high-consequence events (e.g., mine incidents) can be rehearsed without exposing workers to real harm [93]. A similar logic applies to process and utility technicians working in confined spaces, where dedicated IVR platforms [60, 32] treat tanks, silos, underground chambers and manholes as critical sub-infrastructures. These systems guide operators through step-by-step procedures for entry, work and rescue, and explicitly model how geometric configuration, atmospheric conditions and equipment layout define safe and unsafe margins; in addition, they foreground pre-entry preparation by training workers to select appropriate protective equipment and tools before entering the space [32], thereby reducing procedural errors even among trainees with prior formal safety instruction [60]. For hydropower plant operators, immersive training leverages a computational platform for a 132 MW facility [64] to let technicians rehearse operational commands and abnormal procedures under controlled conditions. Within this setting, the machine hall, control room, and access routes are virtualized as task-relevant workspaces, while the simulated plant behavior supports the development of resilience-oriented competences – decision-making, coordination, and constraint management – during grid disturbances and equipment faults. In some implementations, motion-tracking systems and treadmill-based locomotion modules are introduced to replicate operational stress and enhance ergonomic awareness, with the aim of improving both immersion and learning transfer. Related emergency-preparedness drills are also reported for gas-powered plant contexts, where trainees rehearse evacuation and mitigation actions aligned with occupational safety frameworks and standardized safety management principles [103].

A second group of applications targets mobile and specialist technical staff who operate at the interface between infrastructures and their surrounding environment. Within corporate and chemical laboratory settings, VR serious games [118] and inspection environments [75] have been shown to increase attentional absorption and motivation among laboratory staff, safety personnel and compliance actors, encouraging gradual integration with traditional training methods, particularly for senior operators who may be less familiar with game-based interfaces. Importantly, these tools are not limited to generic student audiences: some systems are explicitly designed for operational safety roles, such as Safety and Health Coordinators and laboratory inspectors responsible for periodic inspections and compliance across heterogeneous research facilities [75]. Beyond laboratories, operator-centered VR training is applied to high-risk worksites in which hazards emerge from the interaction of workers, machinery and evolving site configurations. In construction, excavation and roadwork contexts, immersive scenarios train workers to identify, evaluate and respond to hazards on real jobsite layouts [33, 51], and data-structured approaches further encode hazard zones and replay worksite dynamics to improve traceability of unsafe proximities and procedural

deviations during training [68]. Comparable logics recur in geotechnical drilling worksites, where simulations are built around the coordinated actions of drillers and assistants near heavy machinery [83, 104], and in open-pit quarrying, where workers and H&S trainers rehearse safe practices under rapidly changing, equipment-dense conditions [59]. A parallel strand focuses on electrical and maintenance trades, from active construction sites [109] to at-risk technical occupations including wind-turbine service and crane/tower operations [50], where training emphasizes procedural safety, work-at-height constraints and isolation discipline. In PV façade operations, gamified scenarios similarly foreground lockout–tagout routines and role-specific decision-making for cleaning, maintenance and repair personnel [29]. In protection services, immersive environments further extend operator-centered training to structured intervention and coordination tasks, ranging from firefighter operations rehearsed in virtualized building scenarios to complex multi-actor emergency situations that foreground rapid decision-making and role allocation [82, 85]. More marginally, some safety programs also connect operator training ecosystems with risk communication measures aimed at infrastructure users, such as behavioral education to reduce accidents at critical points (e.g., pedestrians in hazardous areas) [86].

In mobility infrastructures, technical personnel must manage systems in motion while safeguarding passengers, freight and crew. For railway personnel, VR-based fire safety training in passenger trains [119] allows drivers and onboard staff to rehearse the management of onboard fires and evacuations in a virtual vehicle interior, reporting high perceived realism and usability, along with improved understanding of operational sequences and crew–passenger interactions. In this context, other studies focus on VR training for locomotive crew [35], combining emergency drills, diagnostic simulation and automated assessment to enhance procedural competence and safety management. Beyond vehicles, tunnel contexts provide a salient example of socio-technical coordination between users, control-room staff, and responders: immersive environments can be used both to rehearse user-side decisions in constrained evacuation conditions and to train intervention teams operating under smoke, limited visibility and evolving hazards, including multi-actor tunnel-fire scenarios [57, 58] and role-differentiated highway-tunnel response platforms spanning control-room operators, emergency teams, and road users [28]. Related transport-oriented systems also explore decision-support configurations at station scale, where digital-twin cores ingest evolving state variables and user actions to support real-time reasoning and operational choices during crisis exercises [108]. Comparable behavioral frameworks have additionally been extended to intentional crisis scenarios through interactive designs that simulate deliberate attacks, broadening preparedness training beyond accidental events [61].

In the maritime domain, the reviewed studies converge on training aimed at shipboard technical operators, with different emphases depending on the operational context. For mooring operations, individual VR training prioritizes dynamic risk assessment and shows favorable outcomes compared to classroom instruction [114]. In the engine room, to reduce procedural ambiguity, a platform combining initial tutorials, virtual guidance and just-in-time feedback supports technical staff and maritime engineers in executing maintenance and safety checklists [122]. For high-voltage shipboard electrical systems, a dedicated simulator promotes safe procedures and behaviors in high electrical-risk scenarios [120]. Fire preparedness is likewise addressed through drill-oriented VR modules aligned with seafarer certification routines, enabling crews to rehearse detection, initial response and evacuation sequences under constrained onboard conditions [110, 126]. In aviation, immersive training targets both pre-flight technical inspection roles and emergency decision-making for operational trainees, extending procedural competence to high-stress, time-constrained scenarios [27, 90]. Across these transport examples, immersive environments help operators internalize standardized procedures and practice real-time decision-making in situations that would be difficult or dangerous to recreate in the field.



Figure 19: VR instructions on how to handle the most common faults in a locomotive for crew training. Reproduced from [35], © 2023 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

Across these strands, studies consistently report higher situational awareness, improved adherence to safety protocols and increased cognitive readiness among technical workers and process operators who train in immersive environments. At the same time, key limitations persist: evaluations often rely on small convenience samples, long-term workplace validation remains scarce, and outcomes frequently focus on usability or short-term learning rather than operational performance. Implementation barriers also include integrating VR into mandatory safety curricula, keeping models aligned with evolving assets and procedures, and ensuring acceptance among experienced workers. Nevertheless, when embedded in existing training ecosystems, immersive applications can bridge complex socio-technical systems and everyday practice, supporting both vertical adaptability across expertise levels and horizontal coordination between field staff, control rooms, and emergency teams.

4.5.3. Building occupants and end-user

Building occupants constitute one of the most heterogeneous and behaviorally influential stakeholder groups within the context of critical infrastructures. They include individuals who work, study, or transit in public buildings such as hospitals, office complexes, and schools. Their actions during emergencies depend on a complex interaction between spatial configuration, functional hierarchies, and individual preparedness, which determines how they perceive risks, interpret cues, and make decisions under stress. Training these users, professionals and non-specialists alike, is essential to ensure both individual safety and collective coordination within complex facilities.

Across the reviewed corpus, two complementary strands emerge: (i) behavioral research using immersive environments to observe and measure occupant responses under controlled conditions; and (ii) training applications, designed to teach and reinforce correct responses and translate simulated experience into preparedness.

The behavioral dimension is exemplified by Lovreglio et al. [95], who reconstruct a seismic scenario in a section of the Auckland City Hospital through VR and BIM to study occupant decision-making. Healthcare facilities are particularly insightful case studies because they combine diverse occupant typologies – doctors, nurses, administrative personnel, and visitors – whose movement patterns and priorities differ sharply. Participants experienced shaking, visual obstruction, and falling debris, allowing researchers to measure evacuation choices and reaction times in a controlled yet realistic setting. This study positions VR as a behavioral observatory, capable of producing empirical data on human responses that inform both emergency planning and architectural design. Building on this foundation, an immersive serious game using the same hospital model was developed [95, 111], shifting the focus from observation to training and preparedness. Here, users actively performed safety actions, such as protective actions (e.g., “drop, hide, cover”), hazard identification and safe route selection, while receiving immediate feedback on their performance. This approach demonstrated how immersive learning strengthens self-efficacy and procedural awareness, showing that VR can serve as a unifying platform for both professional training and public

preparedness within the same infrastructural ecosystem. Similarly, in confined transit infrastructures, the multi-user road-tunnel fire simulator *FréjusVR* [57, 58] trains civilian end-users to rehearse protective actions and evacuation choices under smoke and time pressure; within the same training setting, the impact of avatar representation indicates that switching from “VR-kit-only” proxies to full-body reconstructions affects immersion and social-presence dimensions and is generally preferred for representing the other user during multi-player interactions.

A customizable framework extending this logic to other building types, including offices and administrative complexes, was developed by Feng et al. [107], confirming the scalability of immersive simulations across contexts. At the architectural level, an extensible VR emergency-preparedness framework [116] is proposed as an architecture that can be adapted across scenarios and locations (e.g., workplaces and commercial buildings) to complement conventional drills and scale occupant preparedness. In particular, iterative narrative design (spiral storytelling) encourages reflection and correction in office-based evacuation drills, reinforcing long-term behavioral retention [113].

In educational infrastructures, immersive and mobile VR are applied to simulate emergency scenarios in classrooms and corridors, training teachers and students in evacuation preparedness for earthquake [97, 112] or fire [23, 48, 87, 116]. Complementarily, a VR-based fire-evacuation training model [21] formalizes route safety through an optimal escape-path formulation based on survivability constraints under high temperatures and harmful gases, using it to compare evacuees' choices against safer alternatives and provide feedback. Beyond VR, optical see-through AR fire-safety training for building occupants [76] has been compared against video instruction, showing comparable knowledge acquisition and retention while yielding higher intrinsic-motivation gains and better self-efficacy retention. The experiments show that VR-based exercises produce significant improvements in knowledge retention and behavioral readiness, outperforming traditional paper-based instruction. In online settings, the *Virtual Safety World* [48] delivers knowledge gains comparable to slide-based training while increasing engagement (participants voluntarily spend more time in training), improving one-month retention, and sustaining attention through instrument-based measures. In parallel, Nilsen et al. [18] explored the influence of game mechanics, such as resource richness and avatar customization, on motivation and concentration during serious-game-based learning, while Rahouti et al. [54] introduced adaptive algorithms to dynamically adjust task difficulty and feedback. In the same adaptive direction, metaverse-based building-evacuation training that updates guidance based on real-time information (e.g., crowd distribution and disaster location) outperforms static guidance in evacuation-time savings [23].

Several contributions extend occupant analysis to residential and mixed-use settings under hydro-meteorological hazards. Interactive landslide simulators place users as householders choosing structural and behavioral measures while a simple model shows whether a landslide occurs and how severe it is, allowing analysis of how feedback timing and context shape risk judgements and mitigation preferences [69, 70]. A flood-risk simulation casts learners as floodplain residents who compare protection levels and land-use options, justifying their assessments, focusing on how they construct geohazard arguments [40]. Urban-scale tools built from 360-degree panoramas simulate city-center evacuations and sheltering, recording route choices and times under varied layouts [96], while flood and tsunami preparedness games ask inhabitants of low-lying neighborhoods to identify safe routes, decide when to leave, or allocate limited resources, turning occupant decisions into both training targets and behavioral data [41, 37, 73].

4.5.4. Educators and students

While building occupants engage with immersive technologies primarily as users of infrastructures, educators and students represent a second, distinct stakeholder group: they are learners and knowledge multipliers, central to the diffusion of a safety - oriented culture. In this cluster, immersive technologies serve not only as emergency preparedness tools but also as pedagogical frameworks for shaping the next generation of engineers, architects, and professionals equipped to manage complex systems under risk.

A growing number of studies explore VR and SGs as tools for cognitive empowerment within educational settings, promoting both awareness and professional competence. At the school level, Sukirman et al. [97] developed a mobile VR application for secondary-school students in Indonesia, accessible through low - cost devices such as Google Cardboard. The system trained users in self - evacuation procedures during earthquakes, achieving a 71% improvement in behavioral preparedness and confirming the effectiveness of

mobile VR as a low-cost platform for preventive education and experiential learning. Along the same line, serious games developed for public schools [84] enable pupils to rehearse escape routes and behavioral choices in virtual replicas of their school buildings, consolidating basic rules – use of emergency exits, compliance with signage, avoidance of lifts and hazardous areas – before physical drills. VR-based fire-safety training studies similarly indicate that, even in secondary and technical education, exposure to immersive scenarios can increase individual awareness and perceived self-efficacy in dealing with incipient fires.

Building on this line of research, Feng et al. [112] designed an immersive serious game for a junior secondary school in Australasia, developed through a BIM-Unity workflow and implemented on Oculus Rift. The game simulated an indoor earthquake and post-evacuation scenarios from a first-person perspective, enabling students aged 11-15 to practice realistic responses under stress. The experiment compared three instructional approaches - prior instruction, immediate feedback, and post-game assessment, against a control group trained with leaflets. Results revealed that the post - game assessment condition was the most effective for training children, with greater knowledge acquisition and improved self-efficacy observed [112]. The authors highlighted that IVR SGs help children reflect on their previous behaviors against the feedback they were taking, enhancing retention through a second exposure brought by post - game assessment [112]. An important insight concerns the role of teachers as active facilitators in the learning process [97, 91]. The same platform was used to train educators to guide students during emergency drills, highlighting that immersive simulations not only teach correct actions but also train teachers in leadership, coordination, and risk communication. By enabling instructors to experience and manage virtual emergencies, these tools strengthen the pedagogical dimension of resilience education and empower teachers as mediators between technology and student learning. Complementarily, *FSCHOOL* [94], evaluated with primary-school teachers, shows that VR can be used not only to train pupils but also to strengthen the role of teachers as first safety responsible in the classroom: simulations of prevention, initial extinguishing and evacuation improve procedural knowledge, confidence in their own abilities and motivation to lead students during emergencies. At university level, the *Fire Evacuation Game* [115] likewise confirms the interest of students, academic staff and fire-safety services in gamified evacuation-preparedness formats, while teacher and practitioner evaluations highlight the need for technical support and clear integration with existing learning platforms and emergency plans if such tools are to become a stable component of educational practice rather than isolated experiences.

Hazard-focused applications in schools follow a similar logic while widening the scope to geoscience and hydrometeorological risks. *Volcanology AR* atlases convert static diagrams into interactive 3D models that pupils rotate on mobile devices, with worksheets framing discussion of eruption styles and associated threats [78; 79]. Tropical cyclone and tornado simulators combine handheld AR, desktop visualization, and mixed reality so students can manipulate storm parameters and link changes in track and intensity to learning goals on atmospheric processes and warnings [43; 45; 8]. Tsunami and coastal-flood simulations embed local topography and landmarks into virtual environments so classes walk through inundation in recognizable spaces, strengthening links between concepts, place - based knowledge, and drills [100; 37]. Teachers introduce and debrief these tools, while evaluations address knowledge, interest, and self-efficacy.

In higher education, immersive simulations are increasingly integrated into engineering and safety curricula, fostering professional and analytical competence. Within this context, the spiral - narrative framework developed by Feng et al. [113] was applied to university staff and students, demonstrating how iterative exposure to VR scenarios promotes reflection-in-action, adaptive reasoning, and durable knowledge retention. Through this design, scenarios could be repeated and reflectively re-experienced, allowing learners to adjust their responses based on in - game feedback. The study concluded that immersive serious games can deliver knowledge and enhance self-efficacy as effectively as traditional approaches while offering greater emotional engagement and long - term retention potential. In higher-education programmes, immersive technologies are also used to engage students in tasks that closely resemble professional practice. In engineering and construction courses, multi-device platforms for highway work-zone safety [49] allow students to explore complex sites, recognise hazards and translate their observations into technical reports and formal risk documentation. In experiences such as the “dual hackathon” on flood scenarios [66], students take on quasi-professional roles – designers, risk analysts, coordinators – and, under the guidance of lecturers and tutors, negotiate solutions together with engineers and civil-protection representatives. In these contexts, XR environments do not simply “show” the effects of an extreme event,

but become testbeds for making decisions, comparing perspectives and experimenting with crisis-management roles within a structured educational setting. Such initiatives shift educators from the role of mere content transmitters to that of facilitators of simulated decision-making processes, in which students are asked to act as future professionals and, at the same time, as mediators of risk knowledge for communities and institutions.

At the university level, hazard-related XR environments link disciplinary teaching to emerging risk management roles. Sea-level-rise and flood-risk modules built on game engines and 3D GIS require geography, civil engineering, and environmental science students to interrogate model outputs, combine measures, and justify adaptation choices [99; 36; 25]. Real - world - based immersive VR for volcanology lets students and early-career researchers explore high-resolution outcrop models and landscapes, practising observation and communication in field - like settings without logistical constraints [98]. Flood-preparedness metaverse scenarios and serious games position university learners as crisis coordinators or community leaders who interpret alerts and coordinate basic actions, with outcomes measured through perceived usefulness, presence, and preparedness [123; 73; 121]. These deployments are embedded in courses and hackathons but rarely include practicing CI operators or emergency staff.

Finally, immersive technologies extend to university laboratories and research environments, where they support procedural training and safety management. In [75], VR inspections are used to train safety and health inspectors, laboratory staff, and students in hazard recognition, chemical safety, and compliance, minimizing the need to interrupt real experiments.

These examples show how immersive systems integrate training, assessment, and reflection, offering flexible solutions for both educational and professional contexts. When carefully designed, such environments enable students and teachers to connect technical instruction, behavioral training, and critical reflection within a single learning trajectory. In schools, serious games and VR applications for evacuation and fire management [84, 94, 102, 115] help pupils internalize rules and procedures, while at the same time strengthening the role of teachers as risk mediators and guides during emergencies. In university and professional settings, multi-device platforms and project-based formats such as *x3D training* [49] and *dual hackathons* [66] allow students to rehearse in advance the analytical, decision-making, and communication responsibilities that characterize future roles in safety and critical-infrastructure management. This line of research points to the emergence of a dual pedagogical function of immersive training: on the one hand as a medium for risk education (developing awareness and behavioral competence), and on the other as a professional training tool (developing the analytical, technical, and design thinking of future practitioners). Overall, these studies illustrate that, when immersive environments are grounded in solid educational design principles, they enhance not only cognitive learning but also motivation, reflection, and emotional engagement - key components for developing a lasting culture of safety among educators and students [97, 112, 113]. By linking experiential learning with reflective practice, these approaches transform education itself into a platform for resilience, embedding safety and preparedness within the continuum of lifelong learning.

4.5.5. Citizen and Communities

At the societal level, educational technologies extend beyond professional or educational boundaries to engage citizens and communities in risk awareness and participatory resilience. Simulations designed for public education, and civic - protection campaigns use VR as a communication and awareness tool, translating technical scenarios into accessible narratives that empower individuals to act safely during crises. Such applications emphasize collective learning and social cognition, enabling communities to understand their infrastructural environments, practice emergency behavior, and develop trust in institutional response systems. Within this perspective, citizen-facing applications also address everyday safety in mobility infrastructures: VR training on a railway level crossing [86] supports pedestrians (especially students) in practicing safe crossing behavior and evaluates the experience through the System Usability Scale and sense-of-presence measures. In this sense, VR contributes not only to skill training but to community-based resilience education, reinforcing the shared responsibility between institutions and the public.

Within the hazard-focused set, several serious games and simulations treat citizens and local communities as 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 [37, 41]. Landslide and flood risk simulators have participants adjust slope or defence parameters and justify their choices, allowing researchers to identify misconceptions and shifts in perceived effectiveness of measures [40, 69, 70]. These tools build 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 over structural and non - structural measures, revealing tensions between development, safety, and equity, and the role of trust, experience, and responsibility in shaping preferences [39, 124, 125]. School-centred initiatives connect simulation and drills: in a tsunami project, inundation modelling informs whole - school route revisions and discussions with authorities [72] and, to support scalable preparedness exercises, an urban-evacuation VR training system based on 360° panoramas [96] adopts a lightweight pipeline to represent multi-site escape routes, at the cost of more limited interaction with the virtual environment. While a dual hackathon on immersive simulation convenes student teams, civil protection organizations, and local stakeholders to co-design emergency-training concepts [66]. XR frameworks for flood action and urban risk propose multi-profile environments for user risk training in the urban built environment [56] where residents, volunteers, and responders access role – specific views, but reported pilots remain small and evidence on long-term effects on citizen – institution relations is limited [38, 39, 56, 66, 72, 124, 125].

In parallel, interactive simulations addressing human-induced hazards also contribute to public preparedness. The serious-game scenario of a terrorist attack in a train station [61] exemplifies how immersive design can engage citizens in understanding emergency dynamics and protective decision-making, complementing community-based approaches and extending resilience education to intentional crises.

Overall, the diversity of stakeholders identified in the literature confirms that education technologies have evolved into a meta-paradigm for training on critical infrastructures, uniting technical, cognitive, and social dimensions. Findings converge on three key directions.

- Vertical adaptability: immersive tools can be calibrated to different competence levels, aligning cognitive load with user expertise, from specialists to citizens.
- Horizontal collaboration: multi-role simulations foster cooperation across sectors and professions, reducing communication bottlenecks and improving integrated response capacities.
- Contextual transferability: pedagogical and technical principles validated in one domain (e.g. industry, healthcare, education) can be applied to others, promoting a form of resilience education that transcends sectoral boundaries.

The most innovative and transversal applications, such as [30], exemplify the growing potential of multi-user immersive environments where operators, managers, and responders interact simultaneously within shared virtual spaces. These collaborative systems strengthen situational awareness, coordination, and inter-professional understanding, paving the way for a new generation of evidence-based, human-centered, and inclusive training ecosystems for safety and emergency management.

4.6. Implementation phase

After identifying who learns within resilience - oriented systems, it becomes equally important to understand when and where learning takes place. This section therefore explores the implementation phase of educational technologies across the critical - infrastructure lifecycle, highlighting how different stages, from planning to crisis response, shape pedagogical priorities and technological configurations.

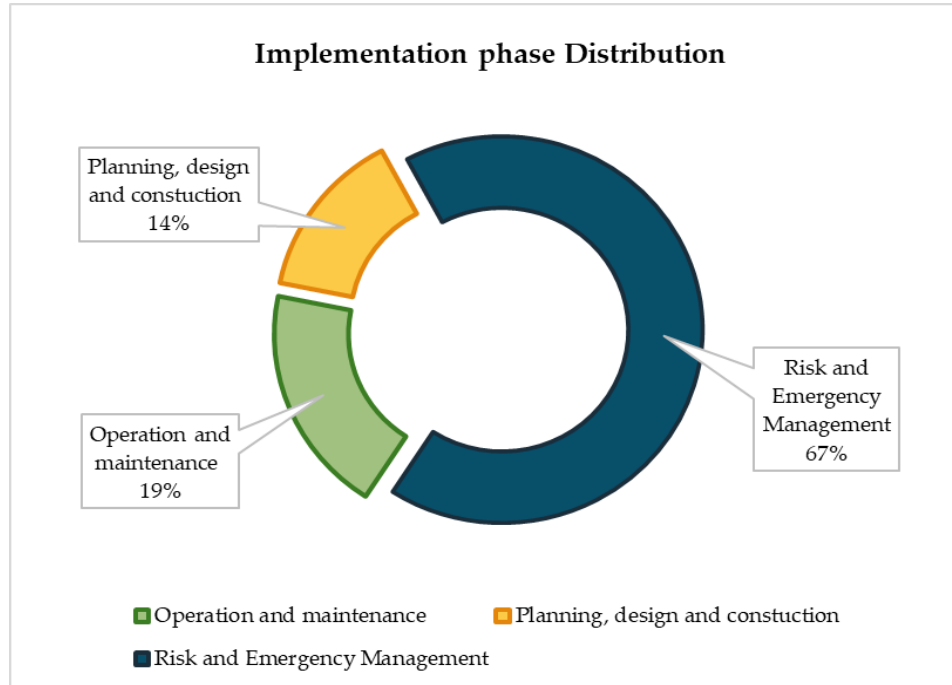


Figure 20: Implementation phase distribution. (Image created by the authors).

4.6.1. Planning, design and construction

During planning, design and construction, critical infrastructures exist primarily as systems in the making: construction sites, excavations, temporary works and workspaces that change over time, where geometric configuration, activity sequencing and the co-presence of equipment and people determine the risk profile. In this context, XR and BIM–VR environments do not merely represent the finished infrastructure; they are used to train workers and technicians on specific tasks before entering the site and to test alternative configurations of spaces, operational phases and procedures.

A first group of applications concerns geotechnical works and construction excavations, treated as temporary underground micro-infrastructure in which excavation volumes, access points and interactions with machinery define risk. In the immersive system for excavation safety [33], two real sites are modelled using terrains generated in Unity, reproducing the position, depth, width and texture of the excavations. In geotechnical drilling simulations [83], the focus shifts instead to the machine–environment relationship: the workspace is segmented into functional and risk zones (drilling area, control area, low-visibility zone, outer area), each associated with specific incident types and access rules. Taken together, these studies show how VR is used to make the “risk geography” of the construction site explicit and to let workers experience hazardous configurations and good practices before exposure in the real field.

A second line of work focuses on the construction of complex vertical infrastructures, in which the sequence of assembly phases is closely intertwined with the risk profile. The simulation proposed by Li et al. [50] breaks down the construction process of a wind tower into successive phases – foundation excavation and casting, reinforcement placement, transport and lifting of tower sections, assembly of nacelle, hub and blades – represented in an immersive VR environment. Throughout the sequence, participants are required to identify the hazards associated with the different construction phases, linking the reading of layout and operations to the systematic assessment of risks.

In continuity with these examples, road and metro work zones are repurposed for training as VR construction scenarios [47, 49, 51, 68], in which risk configurations observed in the field feed exercises in hazard recognition, selection of control measures and discussion of layout variants before their implementation on site.

On the methodological side, comparative studies on the instructional design of VR-based safety training [32] also show that, at this stage, it is not only the realism of the environment that matters, but also the way in which tasks, feedback and errors are orchestrated along the learning sequence, differently influencing the acquisition of declarative knowledge and the willingness to transfer it into practice.

Ultimately, these contributions suggest that the planning, design and especially construction phase constitutes a privileged field for the use of immersive technologies, in which sites, excavations and assemblies are conceived as controlled-risk laboratories. In these laboratories, immersive models both allow safety management practices to be tested and refined and support the creation of initial digital-twin nuclei that can be extended and reused in subsequent operation and maintenance phases.

4.6.2. Operation and maintenance

Operation and maintenance (O&M) are the longest and most knowledge-intensive phases of the infrastructure lifecycle. In these phases, digital and immersive technologies are increasingly used to sustain safety, efficiency, and decision support during routine as well as abnormal conditions. In these stages, training focuses on continuous monitoring, inspection, preventive actions, and the management of anomalies under operational constraints. XR, VR, and digital-twin environments can be understood as controlled, repeatable training and validation platforms where operators rehearse procedures, visualize system status, and anticipate failures without interrupting real operations [26, 59, 104, 106, 114, 118, 120].

Across the reviewed corpus, sector-specific applications show how immersive systems operationalize procedural knowledge and interface literacy. Applications are used to train routine operation, monitoring, and analysis around protective systems. VR tutorials for mobile flood protection units guide trainees through the full assembly sequence of demountable barriers, providing repetition and feedback on time and errors that mirrors real deployment tasks along rivers or dikes [101]. Flood-oriented digital twins and XR dashboards train users to operate observation and decision interfaces: loading scenarios, adjusting sea-level or rainfall inputs, reading water-level and inundation outputs, and checking the status of defenses in 3D GIS scenes [99, 36, 25]. Volcanology field and unrest exercises use VR for analytical work, having students and junior experts inspect virtual outcrops, interpret monitoring time series, and propose alert levels with probabilistic tools, echoing steps in operational surveillance [98, 71].

Comparable solutions emerge in 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 [31, 104, 109, 117, 120]. Operators practice isolation, lock-out/tag-out (LOTO) procedures, circuit testing, and emergency shutdowns under controlled conditions, while data-driven modules record actions and errors for feedback and assessment and, where applicable, certification. Across sectors such as open-cast mining, maritime transport, offshore power systems, chemical laboratories, and aviation, VR and AR-based safety courses similarly guide workers through inspection routines, standardized safety checks, and emergency responses, improving hazard recognition, engagement, and adherence to procedures [26, 27, 29, 59, 89, 104, 105, 106, 109, 114, 118]. Within chemical-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 [75]. Beyond scenario fidelity, controlled comparisons of instructional designs within VR indicate that pedagogically grounded approaches can materially affect learning outcomes: productive-failure-based VR training has been shown to outperform directive-instruction designs in declarative safety knowledge acquisition and retention for confined-space preparation tasks [32]. Evidence syntheses on VR/AR-based safety training underline that these approaches are particularly effective for procedural learning and risk awareness, while calling for more standardized evaluation frameworks and stable integration into organizational training programmes [29, 60]. In transport systems, VR training for locomotive crews enables operators to practice diagnostic procedures and emergency management within interactive digital-twin environments [35]. Fire-related XR systems such as *GUIDE2FR* [65] and tunnel-maintenance simulators [28, 58] link routine inspection with

emergency preparedness, allowing users to monitor sensors, verify alarms, and switch between normal and alert modes within the same digital twin. Taken together, these examples illustrate a functional convergence between maintenance training and safety rehearsal: the same virtual infrastructure supports both preventive management and rapid response.

More advanced approaches incorporate real-time data streams into training environments, moving toward cyber-physical continuity. Oil-depot and hydropower-plant digital twins [30, 64] synchronize IoT sensors, alarms, and control parameters with interactive 3D models, and learning-factory implementations couple digital twins of robot cells and production lines with VR-based operator training [105], providing operators with immediate feedback on equipment status and supporting predictive maintenance strategies. In such contexts, immersive interfaces enable multi-scale understanding, from component to system level, bridging the cognitive gap between monitoring dashboards and physical assets.

Overall, these applications indicate that maintenance and operational training are converging toward integrated, data-informed ecosystems, where continuous learning supports both reliability and emergency readiness. This convergence marks the transition from static maintenance routines to more dynamic resilience management, bridging everyday operations and crisis response.

4.6.3. Risk and Emergency Management

Many applications use XR and serious games to rehearse how people manage risk before and during emergencies [146, 147, 148, 149]. 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 [65]. Complementarily, some studies operate at a planning scale and compare alternative disaster-preparedness strategies in terms of expected effectiveness and health-related impacts [46], while others embed intelligence directly into wayfinding by contrasting dynamic and static guidance to optimize evacuation time and safety [23]. Related VR preparedness frameworks 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 [121].

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 [37, 41, 73]. 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 [40, 69, 70]. 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 [72, 100].

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 [18, 53, 91, 97, 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 [93, 77, 126]. Some drills also couple evacuation with immediate mitigation actions, such as isolating the hazard source as part of the response sequence [103]. Within this stream, drills for occupants and students alternate operational tasks (detecting the fire, selecting escape routes, using extinguishers, and managing distance and time) [115] with more procedural and organizational sequences (roles, evacuation order, collective protocols, and meeting points) [84, 94]. Evaluation encompasses both awareness/competence indicators and scenario performance [102, 116, 48], as well as comparisons across training modalities (e.g., AR versus video) in terms of retention, motivation, and self-efficacy [76], with variants deployed in existing buildings and, in some cases, extended to support search-and-rescue tasks [21, 87, 20]. 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 [119] to naval fire drills up to the muster area [126], and simulators that also support fire-brigade organization and commanding decision-making [110]. 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 [90].

Similar behavioral frameworks have also been applied to human-induced crises, such as the simulation of a terrorist attack [61], 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 [86].

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 [36, 78, 79, 81, 99]. 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 [56] to place-based tsunami drills that train signage interpretation and route choice before real events [96]. In parallel, collaborative multi-hazard environments extend preparedness to intentional crises and support what-if exploration and decision strategies in complex city scenarios [47], while civil-protection initiatives combine emergency simulation and hackathons to develop solutions for communication, coordination, and response support [66]. 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 [36, 39, 123, 124, 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 [28, 38, 66, 77, 96].

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 [57, 58]. 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 [28]. 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 [24]. 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 [34]. Related patterns recur in firefighter training on real buildings for preparedness and intervention [82], complex scenarios that require multi-agency coordination and rapid decision-making [85], industrial contexts such as oil depots that combine preventive inspection with multi-role drills and penalties for errors and delays [30], and systems that introduce automation/robotics to guide action and support personnel assessment [22], as well as low-frequency/high-risk events in constrained environments such as mines [93].

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 [56, 74, 121]. 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 [92].

5. Discussion

Across the reviewed corpus, the convergence of educational, technological, and infrastructural dimensions reveals a profound transformation in how resilience and risk management are conceived within the field of critical infrastructures. What emerges is a shift from isolated training applications toward integrated learning ecosystems where simulation, data, and human interaction coalesce into dynamic environments for experiential and adaptive learning. These ecosystems blur the boundaries between education, operation, and governance, making training an ongoing process rather than a discrete activity. Immersive environments—whether VR, AR, or hybrid XR configurations—function not merely as didactic tools but as cognitive infrastructures that reproduce the systemic complexity, temporal dynamics, and interdependencies of real operations. Within this paradigm, learning occurs through enactment and reflection: users do not only practice procedures but experience the constraints, coordination logics, and emotional conditions of real emergencies. In this sense, the pedagogical value of simulation lies less in its realism per se than in its ability to embed learners within the logic of systemic interdependence that defines critical infrastructures.

The synthesis across technological layers shows a clear evolution from static, rule-based simulations toward adaptive, data-driven, and multi-user architectures that approach the logic of cyber-physical systems. Rule- and knowledge-based engines remain valuable where procedural consistency and formal verification are essential, yet they are increasingly complemented by agent-based, AI-enhanced, and digital-twin frameworks capable of reproducing feedback loops between environment and behavior. This progression mirrors the digital transformation of the infrastructures themselves: as assets become sensorized and interconnected, their virtual counterparts evolve from training simulators into living laboratories for operational learning. On the interaction side, the continuum extends from non-immersive desktop interfaces to fully embodied and collaborative metaverse systems, each level calibrated to a specific balance of accessibility, realism, and coordination. While visual immersion enhances presence and engagement, cognitive immersion—the capacity to reason, decide, and collaborate under uncertainty—emerges as the real driver of learning transfer. In this respect, multi-user and metaverse environments mark a decisive turning point, enabling collective rehearsal, inter-agency coordination, and distributed situational awareness across domains once trained separately.

At the same time, significant limitations persist that prevent the full realization of this vision. Cultural and institutional barriers remain among the most critical: immersive technologies are often perceived as experimental or peripheral, and their integration into formal curricula or regulatory frameworks is still fragmentary. Experienced professionals may show skepticism toward game-like interfaces, while academic institutions and public agencies struggle to maintain continuity between pilot projects and operational adoption. Methodological limitations further constrain progress. Evaluation is predominantly focused on usability and short-term engagement, rarely extending to behavioral validation, longitudinal retention, or transferability to real-world performance. Metrics capable of quantifying resilience-related learning outcomes—such as situational awareness, decision accuracy, or adaptive collaboration—are still embryonic. Technological constraints also play a role: interoperability between XR platforms, BIM or GIS datasets, and real-time sensor streams remains inconsistent, and the rapid obsolescence of hardware and software threatens the sustainability and reproducibility of training assets. A neglected yet crucial issue concerns the preservation of digital learning experiences: 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 once technologies or operating systems evolve. In this sense, the fragility of digital products mirrors the fragility of the infrastructures they aim to protect, underscoring the need for robust strategies of conservation, metadata standardization, and open access to simulation datasets.

Looking ahead, the future of resilience education will depend on the capacity to integrate technological sophistication with human-centered design and evaluative rigor. Three strategic directions emerge. First, there is a need to establish shared assessment frameworks that go beyond usability and motivation, linking learning analytics with performance indicators that reflect real operational competence. Second, adaptive intelligence—enabled by AI and data analytics—should be leveraged not only for scenario realism but for personalized learning trajectories that accompany operators throughout their careers, connecting training data to actual performance metrics within digital-twin environments. Third, sustainability must become a

design principle: immersive products should be conceived as part of living repositories of collective knowledge, interoperable across institutions, hazards, and technologies. The challenge is therefore dual: technological, in maintaining the longevity and adaptability of virtual systems, and cultural, in fostering interdisciplinary literacy and openness to continuous learning.

In sum, the reviewed literature confirms that immersive and data-driven education has the potential to redefine how societies prepare for, respond to, and learn from crises affecting critical infrastructures. Yet its consolidation as an evidence-based practice will depend on long-term commitment to evaluation, preservation, and inclusivity. The transition from experimental simulation to institutional learning infrastructure requires bridging the gap between innovation and governance, ensuring that every digital experience produced today contributes to the cumulative intelligence of tomorrow's resilient operators.

6. Conclusions

Digital transformation, increased systemic risks and the growing complexity of critical infrastructure require a redefinition of the role of professionals engaged in asset management. In this context, the figure of the Resilient Operator [13,14,15] emerges: a worker who is not only capable of managing assets and processes, but also of adapting, learning, and reacting effectively to new challenges and work ecosystems. This concept resonates strongly with recent discussions on Construction 5.0 and Operator 5.0, where the evolution of industrial paradigms emphasizes human - centricity, sustainability, and resilience. The Resilient Operator can thus be interpreted as the critical infrastructure counterpart of Operator 5.0, embodying the fusion between human expertise and machine efficiency. In this vision, operators are no longer passive executors but active co - creators of resilient systems, able to collaborate with advanced technologies - digital twins, AI, IoT, and automation - while preserving the centrality of human judgment and adaptability. Recent literature also highlights that the COVID - 19 pandemic exposed the fragility of existing manufacturing and infrastructure systems, underscoring the workforce as both the most agile and most vulnerable resource. Making human operators more resilient - through training, education, and systemic support - becomes the cornerstone of building organizations capable of withstanding disruptions. The Resilient Operator 5.0 paradigm, developed in the context of Industry 5.0, demonstrates how resilience must be framed not only at the technological or systemic level, but also at the human one, strengthening cognitive, emotional, and collaborative dimensions alongside technical expertise. Within the critical infrastructure domain, the Resilient Operator thus emerges as a new professional paradigm, bridging tradition and innovation, and combining established technical skills with the flexibility, agility, and cross - domain awareness required by today's contexts. Their training and development represent the most advanced outcome of reskilling and upskilling programmes supported by Education Technology.

7. 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
IoT	Internet of Things
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
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 "augmented reality" OR "mixed reality" OR "extended 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 (EXCLUDE(SUBJAREA,"MEDI") OR EXCLUDE(SUBJAREA,"IMMU") OR EXCLUDE(SUBJAREA,"VETE") OR EXCLUDE(SUBJAREA,"DENT") OR EXCLUDE(SUBJAREA,"PHAR") OR EXCLUDE(SUBJAREA,"NEUR") OR EXCLUDE(SUBJAREA,"NURS")))

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Annex 2



GLOSSARIO



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3D MODEL

IT Un modello 3D (modello tridimensionale) è una rappresentazione matematica di un oggetto tridimensionale. È un elemento chiave della computer grafica 3D, del disegno industriale, della progettazione architettonica e della stampa tridimensionale. Il processo che riguarda la creazione di un modello 3D, è detto modellazione 3D (modellazione tridimensionale), è il processo atto a definire una forma tridimensionale in uno spazio virtuale generata su computer. Che si distingue da altri tipi di modellazione tridimensionale, come ad esempio la scultura tradizionale.

EN A 3D model (three-dimensional model) is a mathematical representation of a three-dimensional object. It is a key element of 3D computer graphics, industrial design, architectural design and three-dimensional printing. The process of creating a 3D model is called 3D modeling (three-dimensional modeling), it is the process of defining a three-dimensional shape in a virtual space generated on a computer. Which is distinct from other types of three-dimensional modeling, such as traditional sculpture.

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ARTIFICIAL INTELLIGENCE

IT Il termine Intelligenza Artificiale (IA) è stato coniato più di 50 anni fa e viene usato per indicare sistemi in grado di simulare l'intelligenza umana e risolvere problemi tipicamente riservati all'uomo. Più che di una vera e propria intelligenza la IA è un sistema razionale, che cerca risposte a quesiti specifici sfruttando processi di addestramento in grado di auto migliorarsi.

EN The term Artificial Intelligence (AI) was coined more than 50 years ago and is used to refer to systems capable of simulating human intelligence and solving problems typically reserved for humans. Rather than true intelligence, AI is a rational system that seeks answers to specific questions by leveraging training processes that can improve themselves over time.

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AUGMENTED REALITY

- IT** L'Augmented Reality (AR) è una tecnologia che combina oggetti virtuali 3D con il mondo reale in tempo reale. Questo è possibile grazie all'aggiunta di contenuti generati dal computer, come immagini, suoni o dati, a ciò che vediamo. Migliora il modo in cui percepiamo e interagiamo con l'ambiente circostante. Nel corso degli anni, la realtà aumentata è avanzata considerevolmente e oggi viene utilizzata in molti settori, come l'educazione, l'intrattenimento e diverse industrie.
- EN** Augmented Reality (AR) is a technology that combines 3D virtual objects with the real world in real time. This is possible by adding computer generated content like images, sounds, or data to what we see. It improves how we perceive and interact with our surroundings. Over the years, augmented reality has advanced considerably and it is now being used in many areas, such as education, entertainment and across different industries.

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AVATAR

- IT** L'Avatar è una rappresentazione virtuale 2D o 3D personalizzata di un'identità fisica in un ambiente digitale, la sincerità della figura non costituisce un obbligo. Può rappresentare una persona reale o un'intelligenza artificiale, come personaggi non giocanti o assistenti virtuali, e svolge un ruolo cruciale nel riconoscimento e nell'interazione tra utenti. Gli avatar trovano applicazione in vari contesti, dai videogiochi ai mondi virtuali non ludici, social network e ambienti di lavoro digitali.
- EN** An Avatar is a personalized 2D or 3D virtual representation of a physical identity in a digital environment; the figure's sincerity is not a requirement. It can represent a real person or an artificial intelligence, such as NPCs (Not Playable Character) or virtual assistants, and plays a crucial role in user recognition and interaction. Avatars find application in a variety of contexts, from video games to non-gaming virtual worlds, social networks, and digital work environments.

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BIM

IT Il BIM (Building Information Modeling) è un insieme di metodologie basate su processi digitali per la creazione e la gestione di dati su edifici e infrastrutture, durante il loro intero ciclo di vita, che consente una collaborazione multidisciplinare tramite un modello 3D condiviso. Integrando informazioni geometriche e semantiche, il modello stesso diventa un database di tutti i dati rilevanti di un progetto, supportando un migliore processo decisionale, efficienza dei costi e gestione dei rischi, dalla progettazione preliminare alla dismissione.

EN BIM (Building Information Modeling) is a set of methodologies based on digital processes for creating and managing data about buildings and infrastructure, throughout their entire lifecycle, enabling multi-disciplinary collaboration via a shared 3D model. By integrating geometrical and semantic information, the model itself becomes a database of all the relevant data of a project, supporting better decision-making, cost efficiency, and risk management, from initial design to decommissioning.

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DIGITAL TWIN

IT Una rappresentazione virtuale dinamica e ad alta fedeltà di oggetti fisici, sistemi o processi, aggiornata in tempo reale con dati raccolti da AI, IoT, sensori e tecnologie avanzate. Consente simulazioni, monitoraggio e ottimizzazione, migliorando efficienza, sostenibilità e sicurezza. Nell'Industria 5.0 evolve in Human Digital Twin (HDT), integrando benessere umano, emozioni e strumenti come BIMtoBEM, XR e blockchain per una produzione resiliente e umanocentrica.

EN A dynamic and high-fidelity virtual representation of physical objects, systems, or processes, updated in real-time with data from AI, IoT, sensors, and advanced technologies. It enables simulations, monitoring, and optimization, improving efficiency, sustainability, and safety. In Industry 5.0, it evolves into the Human Digital Twin (HDT), integrating human well-being, emotions, and tools like BIMtoBEM, XR, and blockchain for resilient, human-centered production.

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E LEARNING

IT L'eLearning si riferisce all'uso di tecnologie elettroniche per accedere a contenuti educativi al di fuori di un'aula tradizionale. Comprende una varietà di formati, tra cui corsi online, classi virtuali e strumenti di collaborazione digitale, permettendo agli studenti di apprendere da remoto e con i propri ritmi. Questo approccio sfrutta risorse multimediali, valutazioni interattive e piattaforme di comunicazione per facilitare l'apprendimento. L'eLearning è diventato una strategia chiave nell'istruzione superiore per migliorare i risultati educativi e stimolare la motivazione degli studenti.

EN eLearning refers to the use of electronic technologies to access educational curriculum outside of a traditional classroom. It encompasses a variety of formats, including online courses, virtual classrooms, and digital collaboration tools, enabling learners to study remotely and at their own pace. This approach leverages multimedia resources, interactive assessments, and communication platforms to facilitate learning. eLearning has become a key strategy in higher education to enhance educational outcomes and stimulate student motivation.

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ENGAGEMENT

IT L'engagement nella realtà virtuale (VR) è il livello di coinvolgimento emotivo, cognitivo e fisico dell'utente durante l'interazione con ambienti virtuali. Questo concetto è fondamentale per valutare l'efficacia delle esperienze VR: un alto engagement può ridurre lo stress e migliorare l'apprendimento. Realismo, interattività, immersione e coinvolgimento emotivo giocano un ruolo chiave nel rendere le esperienze VR funzionali e memorabili, soprattutto quando progettate per suscitare emozioni e favorire l'interazione attiva.

EN Engagement in virtual reality (VR) is the level of emotional, cognitive, and physical involvement of the user during interaction with virtual environments. This concept is crucial for assessing the effectiveness of VR experiences: high engagement can reduce stress and improve learning. Realism, interactivity, immersion, and emotional involvement play a key role in making VR experiences functional and memorable, especially when designed to evoke emotions and encourage active interaction.

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EXPERIENTIAL LEARNING

IT L'apprendimento esperienziale è un processo educativo che si basa sull'esperienza diretta, coinvolgendo aspetti cognitivi, emotivi e sensoriali. In questo modello pedagogico, lo studente contribuisce attivamente alla costruzione della conoscenza attraverso l'interazione, la riflessione e l'applicazione pratica. Questo approccio sviluppa capacità di problem-solving, stimola la creatività e accresce l'autoconsapevolezza, migliorando atteggiamenti e comportamenti grazie all'auto-osservazione e all'osservazione esterna.

EN Experiential learning is an educational process based on direct experience, involving cognitive, emotional, and sensory aspects. In this pedagogical model, the student actively contributes to the construction of knowledge through interaction, reflection, and practical application. This approach develops problem-solving skills, stimulates creativity, and enhances self-awareness, improving attitudes and behaviors through self-observation and external observation.

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EXTENDED REALITY

IT Termine emergente che include in maniera generica tutte le tecnologie immersive in grado di generare o modificare la realtà ampliando i confini della percezione umana. Tra queste si annoverano la Realtà Virtuale (VR), la Realtà Aumentata (AR) e la Realtà Mista (MR). Secondo alcuni esperti del settore, il termine "estesa", per definizione, escluderebbe la VR, poiché in quest'ultima la realtà non viene estesa, bensì sostituita. Per questa ragione, xReality (XR) potrebbe essere ritenuto un termine più appropriato, dove "x" funge da segnaposto per qualsiasi forma di nuova realtà.

EN An emerging umbrella term that encompasses all immersive technologies capable to generate or modify reality expanding the limits of human perception. These include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). According to some industry experts, the term "extended" would, per definition, exclude VR, as in VR, reality is not extended but rather replaced. For this reason, xReality (XR) could be considered more appropriate term, where "x" serves as a placeholder for any form of new reality.

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GAMIFICATION

IT La gamification è l'applicazione di elementi e dinamiche tipiche del gioco in contesti non ludici, come l'edilizia e le infrastrutture, per aumentare il coinvolgimento e la motivazione degli utenti. Integrando la gamification con tecnologie come il Building Information Modeling (BIM), la realtà virtuale (VR) e la realtà aumentata (AR), è possibile migliorare la formazione degli utenti in progetti complessi simulando molteplici scenari in modo immersivo. La VR e l'AR consentono agli utenti di interagire con modelli digitali in ambienti realistici, rendendo più intuitivo il processo decisionale e l'addestramento. Ad esempio, si possono creare simulazioni per la formazione sulla sicurezza o per ottimizzare il flusso di lavoro in cantiere.

EN Gamification is the application of typical game elements and dynamics in non-gaming contexts, such as construction and infrastructure, to increase user engagement and motivation. By integrating gamification with technologies like Building Information Modeling (BIM), Virtual Reality (VR), and Augmented Reality (AR), it is possible to enhance user training in complex projects by simulating multiple scenarios in an immersive way. VR and AR allow users to interact with digital models in realistic environments, making decision-making and training more intuitive. For example, simulations can be created for safety training or to optimize workflow on construction sites.

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HEAD - MOUNTED DISPLAYS

IT Un HMD è un dispositivo indossabile sulla testa, generalmente un casco o degli occhiali, che, con l'ausilio di un sistema di tracciamento, consente a un utente la percezione senza soluzione di continuità di un ambiente virtuale in un campo visivo variabile che va da 110° a 130°. Questi dispositivi sono dotati di due schermi, uno per ciascun occhio, che presentano due immagini differenti renderizzate in base alla visione di ogni occhio. Questo fornisce segnali di profondità binoculare realistici.

EN An HMD is a head-mounted device, usually a helmet or goggles, that uses a tracking system to provide the user with seamless perception of a virtual environment in a variable field of view ranging from 110° to 130°. These devices are equipped with two screens, one for each eye, which present two different images, rendered according to the vision of each eye. This provides realistic binocular depth signals.

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- <https://www.treccani.it> HMD in Enciclopedia (accessed 24/01/2025)

IFC

IT Schema di dati standardizzato aperto (ISO 16739-1:2024) sviluppato da buildingSmart per promuovere la metodologia openBIM e migliorare lo scambio e la condivisione di dati provenienti da modelli parametrici. Codifica l'identità, le caratteristiche e le relazioni di oggetti, concetti astratti (es: performance e costing), processi e persone nel settore delle costruzioni e del Facility Management, migliorando l'interoperabilità tra diversi software BIM.

EN The standardized open data schema (ISO 16739-1:2024) developed by buildingSmart aims to promote the openBIM methodology and improve the exchange and sharing of data from parametric models. It encodes the identity, characteristics, and relationships of objects, abstract concepts (e.g., performance and costing), processes, and people in the construction and Facility Management sectors, enhancing interoperability between different BIM software.

References:

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IMMERSIVE VIRTUAL ENVIRONMENT

IT Un ambiente virtuale immersivo (AVI) è uno spazio simulato creato da tecnologie come VR, AR e MR, che offre esperienze interattive e coinvolgenti. Grazie a visori, cuffie e interfacce tattili, l'utente esplora scenari tridimensionali, stimolando vista, udito e tatto. Le caratteristiche principali includono immersione sensoriale, interattività, personalizzazione, sicurezza e feedback immediato, supportando un apprendimento esperienziale sicuro e competenze come pensiero critico e comunicazione.

EN An immersive virtual environment (IVE) is a simulated space created using technologies such as VR, AR, and MR, designed to offer interactive and engaging experiences. Using headsets, spatial audio, and haptic interfaces, users explore 3D scenarios, stimulating sight, hearing, and touch. Key features include sensory immersion, interactivity, personalization, safety, and immediate feedback, supporting safe experiential learning and skills such as critical thinking and communication.

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METaverse

IT Il metaverso è un ecosistema digitale interoperabile di ambienti 3D immersivi, accessibili in tempo reale da una molteplicità di dispositivi. Gli utenti interagiscono tramite identità digitali dette avatar, con esperienze sincrone e persistenti anche in loro assenza. Eventi, oggetti e identità digitali si mantengono nel tempo. Favorisce interazioni sociali, economiche e culturali. Si basa su tecnologie abilitanti della X-Reality come realtà virtuale, aumentata e mista.

EN The metaverse is an interoperable digital ecosystem of immersive 3D environments, accessible in real time from multiple devices. Users interact through digital identities called avatars, enjoying synchronous and persistent experiences even when they are offline. Events, objects, and digital identities endure over time. It fosters social, economic, and cultural interactions. It relies on X-Reality enabling technologies such as virtual, augmented, and mixed reality.

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MIXED REALITY

IT Concetto in continua evoluzione, privo di una definizione universalmente concordata, evoca ambienti di diversa natura in cui oggetti reali e virtuali, e i loro dati, coesistono e interagiscono in tempo reale all'interno di un'unica interfaccia. Introdotta per la prima volta nel contesto del Vitruality Continuum (VC) per indicare tutte le sfumature presenti tra un ambiente completamente reale ed una totalmente virtuale. In funzione della quantità di oggetti reali e virtuali nell'ambiente, si distinguono stadi intermedi come la Realtà Aumentata (AR) e la Virtualità Aumentata (AV). Studi recenti propongono l'AR-Continuum basato sul grado di "presenza locale": maggiore è l'integrazione percepita dall'utente del contenuto virtuale all'interno dell'ambiente ibrido, più ci si avvicina alla Realtà Mista; al contrario, quando il contenuto è una semplice sovrapposizione si parla di Realtà Assistita.

EN An evolving concept, it evokes a variety of environments in which real and virtual objects, and their data, coexist and interact in real time within a single interface. The term was first introduced in the context of the Vitruality Continuum (VC) to indicate all the nuances present between a fully real and a fully virtual environment. Depending on the amount of real and virtual objects in the environment, intermediate stages such as Augmented Reality (AR) and Augmented Virtuality (AV) are distinguished. Recent studies propose an AR-Continuum based on the degree of 'local presence': the greater the perceived integration of the virtual content in the physical environment, the closer one gets to Mixed Reality; on the contrary, when the content is merely superimposed, one speaks of Assisted Reality.

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MOTION SICKNESS

IT La chinetosi, o motion sickness, è una condizione caratterizzata da una sensazione di malessere provocata dal movimento, reale o virtuale, che si verifica spesso durante viaggi o immersioni in realtà virtuale. I sintomi includono nausea, vomito, pallore, sudorazione, ipersalivazione e la cosiddetta sindrome di sopite (sonnolenza e affaticamento). Le cause precise e i meccanismi neurobiologici restano incerti, ma l'ipotesi del conflitto sensoriale è la più accreditata. La suscettibilità varia tra individui, influenzata da fattori genetici, ambientali e dalla privazione del sonno.

EN Motion sickness is a condition characterized by a feeling of discomfort caused by real or virtual motion, often occurring during travel or virtual reality immersion. Symptoms include nausea, vomiting, pallor, sweating, hypersalivation and the so-called sopite syndrome (drowsiness and fatigue). The accurate causes and neurobiological mechanisms remain uncertain, but the sensory conflict hypothesis is the most widely accepted. Susceptibility varies among individuals, influenced by genetic, environmental factors, and sleep deprivation.

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OPENBIM

IT OpenBIM è un processo collaborativo e neutrale che estende i benefici del BIM. La differenza principale tra queste due metodologie risiede nell'interoperabilità: mentre il BIM spesso impiega formati proprietari "chiusi" che possono limitare la compatibilità tra software, openBIM adotta standard "aperti", come IFC, potenziando la condivisione dei dati tra diversi software e stakeholder e migliorando l'efficienza dei progetti e degli asset durante tutto il loro ciclo di vita.

EN OpenBIM is a collaborative and neutral process that extends the benefits of BIM. The main difference between these two methodologies lies in interoperability: while BIM often uses proprietary "closed" formats that can limit compatibility between software, openBIM adopts "open" standards, such as IFC, enhancing data sharing among different software and stakeholders, and improving the efficiency of projects and assets throughout their lifecycle.

References:

- <https://www.buildingsmart.org/>

VIRTUAL REALITY

IT La Realtà Virtuale (VR) è una tecnologia che simula uno spazio tridimensionale immersivo creato digitalmente, che può essere simile o completamente diverso dal mondo reale. L'utente può muoversi nell'ambiente virtuale, esplorarlo da diversi punti di vista e interagire con esso per mezzo di interfacce non convenzionali, quali occhiali e caschi su cui viene rappresentata la scena ed eventuali dispositivi per la riproduzione di suoni, la simulazione di stimoli tattili e la traduzione di movimenti reali in istruzioni per il software.

EN Virtual Reality (VR) is a technology that simulates a digitally created immersive three-dimensional space that can be similar to or completely different from the real world. The user can move through the virtual environment, explore it from different angles and interact with it by means of unconventional interfaces, such as goggles and helmets on which the scene is represented and possible devices for reproducing sounds, simulating tactile stimuli and translating real movements into instructions for software.

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VR PERIPHERALS

IT Le periferiche VR sono dispositivi hardware progettati per offrire un'esperienza immersiva in realtà virtuale, consentono all'utente di interagire con l'ambiente virtuale e di percepire sensazioni che si avvicinano molto alla realtà. Comprendono: dispositivi di visualizzazione (come i visori VR), dispositivi di input (quali controller e guanti aptici), sistemi di feedback sensoriale (come tute aptiche e pedane), e dispositivi di tracking (sensori e telecamere).

EN VR peripherals are hardware devices designed to provide an immersive virtual reality experience; they allow the user to interact with the virtual environment and perceive sensations that closely approximate reality. They include: display devices (such as VR viewers), input devices (such as controllers and haptic gloves), sensory feedback systems (such as haptic suits and footpads), and tracking devices (sensors and cameras).

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Annex 1

Abstract

The growing complexity and interdependence of critical infrastructures, increasingly exposed to natural and technological hazards, call for innovative educational approaches to enhance resilience and risk management. This study examines global trends, research patterns, and challenges in integrating digital and immersive technologies into education and training for professionals and communities engaged in critical infrastructures management. A systematic review of peer - reviewed literature was conducted, analyzing a corpus of studies across six dimensions: technological approach, pedagogical model, hazard typology, infrastructure domain, stakeholder category, and implementation phase. The analysis reveals a growing shift from traditional 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 the widespread adoption of these innovations. The findings underscore that digital and immersive technologies are pivotal to reconfiguring education and training frameworks, enabling the formation of Resilient Operators endowed with adaptive cognition, continuous learning capacities, and effective 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 (CIs) 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, 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].

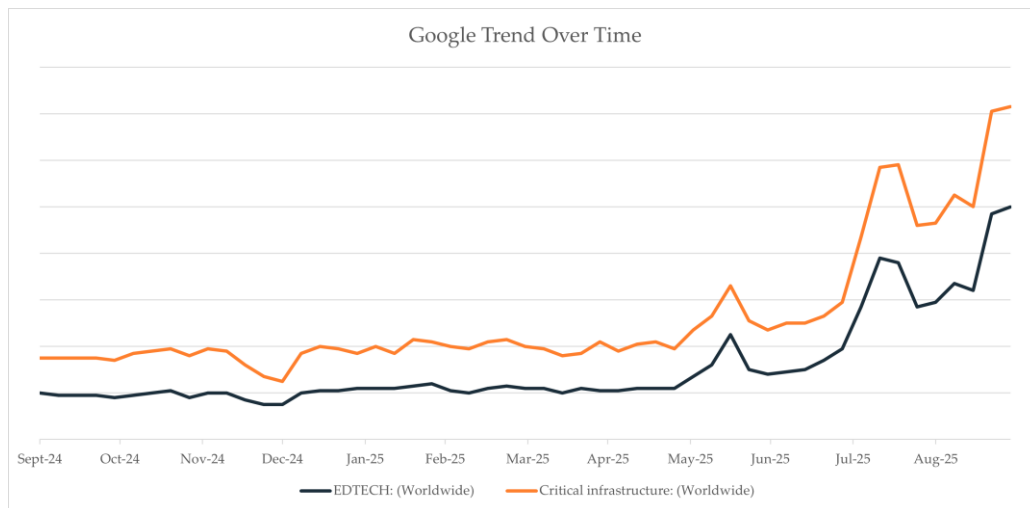


Figure 1: Evolution of global search interest in “EdTech” and “Critical Infrastructure” over time.

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.

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.

Specifically, this review investigates how academic research and applied initiatives address four interrelated dimensions:

- the integration of Educational Technologies into professional training;
- the evolution of pedagogical models in technical and engineering education;
- the role of stakeholders and institutions in promoting adaptive learning ecosystems;
- the development of competencies that underpin resilience and systemic awareness.

By critically analyzing studies across different technological, disciplinary, and geographical contexts, the review seeks to provide insights for rethinking education on critical infrastructure, guiding future research and policy development.

The following sections detail the methodological approach adopted (Section 2) and the paper analyzed (Section 3), explore the educational and technological challenges (Sections 4), and discuss emerging trends and future directions (Sections 5).

2. METHODOLOGICAL APPROACH TO RESEARCH

This literature review adopts a systematic and interpretative approach to explore how education, training, and capacity building are evolving in the field of Critical Infrastructure management. The goal is to identify trends, challenges, and opportunities emerging from the intersection of digital transformation, resilience - oriented governance, and educational innovation.

Following the guidelines for systematic reviews in multidisciplinary research, the process combined quantitative and qualitative methods:

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

The review procedure consisted of five main phases: (i) definition of research questions; (ii) search and retrieval of publications; (iii) screening and eligibility assessment; (iv) data extraction and classification; and (v) interpretative synthesis and validation.

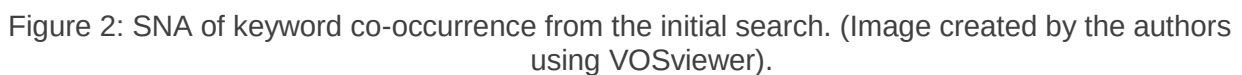
2.1. Research Approach

Given the multidisciplinary nature of the topic, the review follows a mixed quantitative - qualitative approach, combining elements of systematic literature review and narrative synthesis. This dual strategy allows for both the identification of quantitative patterns, such as the distribution of research by technology, domain, or geographical area, and the qualitative interpretation of theoretical frameworks, educational models, and pedagogical practices.

The review was designed to answer the following guiding questions:

1. Technological Integration - How are emerging digital and immersive technologies (e.g., VR, AR, XR, Digital Twins, AI - based platforms) being integrated into education and training programs for critical infrastructure management?
2. Applications in Critical Infrastructure sectors - In which CI domains (e.g., energy, transport, water, healthcare, communication) are these technologies applied, and what are their objectives, methods, and measurable outcomes?
3. Applications in hazard contexts - In which hazard scenarios (e.g., natural, technological, or hybrid events such as earthquakes, floods, fires, or cyber incidents) are these technologies applied, and how do they contribute to enhancing preparedness, risk awareness, and adaptive response?
4. Stakeholders and target groups - Who are the primary stakeholder categories (e.g., operators, engineers, decision - makers, emergency responders, citizens) involved in these educational initiatives, and how are their learning needs differentiated?
5. Pedagogical frameworks - Which educational frameworks, instructional strategies, and learning models (e.g., experiential learning, problem - based learning, serious gaming) are most frequently adopted to support technology - enhanced training in CI resilience?
6. Skills and competencies - What competencies are prioritized in reskilling and upskilling programs for the CI workforce in response to digital transformation and system interconnectivity?
7. Research gaps and future directions - What knowledge gaps, methodological limitations, and research opportunities can be identified across CI sectors regarding the use of Educational Technologies for resilience - building?

These questions guided the structure of the analytical framework, enabling the mapping of technological and pedagogical trends across CI sectors and the identification of gaps in resilience - oriented education.



The configuration of clusters and connections was used to refine the final search query: central, well-connected clusters that intersect education, risk, and advanced technologies were prioritised, while loosely connected or isolated clusters guided the exclusion of domains outside critical-infrastructure-oriented training.

Developing a reliable search query in the field of CI proved particularly challenging due to the polysemy and domain overlap of several key terms. Words such as bridge, tunnel, or station, which are fundamental for describing physical infrastructures, also appear in unrelated contexts (e.g., “data bridge,” “neural tunnel,”

“communication station”), thus generating noise in the search results. Conversely, the term training, essential within the educational scope, frequently occurs in computer science literature in reference to data training or machine learning pipelines, greatly expanding the retrieved corpus without contributing to the intended educational focus.

In parallel, while terms such as building or construction are overrepresented in the architectural and engineering literature, the expression critical infrastructure itself is notably underused in titles, abstracts, and keywords, even when the content clearly addresses systems that fall within this definition. To compensate for this semantic gap, the search strategy incorporated an extended list of sector - specific keywords (e.g., energy, transport, water, health, ICT, communication, industrial facilities) representing the main CI typologies recognized in international classifications. Although this strategy ensured broad coverage, it may have inadvertently excluded less conventional or emerging infrastructure categories.

This refinement of the search string was therefore an essential methodological step to balance recall and precision, ensuring that the corpus accurately reflected research positioned at the intersection of education, technology, and resilience, without being diluted by unrelated computational or construction - oriented studies.

The temporal window was defined to capture the decade of major expansion in immersive and simulation - based learning research. Initial screening was performed by reading titles and abstracts to ensure relevance to both educational and resilience domains, removing duplicates and off - topic entries before full - text analysis.

Despite these refinements, a certain degree of terminological variability remains intrinsic to the field of critical infrastructure studies. This linguistic heterogeneity, further discussed in Section 2.6 Limitations, inevitably affects retrieval precision and should be considered when interpreting the scope of the reviewed corpus.



Table1 - Domains and relevant keywords for search queries.

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
2015 - 2026 (PUBYEAR > 2014 AND PUBYEAR < 2027, inclusive)			
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

Drawing on the SNA mapping, candidate keywords are grouped into four domains: scenario-based education and training, immersive and interactive digital technologies, crises and natural hazards, and critical infrastructure/contextual settings. Table 1 consolidates these domains with representative keywords and search fields, translating the conceptual clusters into an operational Boolean query. This structuring sharpens the search strategy toward the intersection of training, advanced technologies, hazards, and CI contexts, while constraining retrieval from loosely related educational or engineering areas.

2.3. Inclusion and Exclusion Criteria

Studies were selected according to the following criteria:

Inclusion criteria:

- Peer - reviewed journal articles, conference papers, and book chapters focusing on education, training, or workforce development related to CI sectors (e.g., energy, transport, water, health, ICT);
- Studies presenting or analyzing the application of digital, immersive, or simulation technologies in educational or operational training contexts;
- Contributions explicitly addressing resilience, risk management, or system reliability in conjunction with learning methodologies;
- Research providing empirical data, methodological frameworks, or conceptual analyses relevant to CI learning ecosystems.

Exclusion criteria:

- Publications with a purely technical or engineering focus without educational implications;
- Papers not related to critical infrastructures or workforce development;
- Studies concerning medical, clinical, or COVID - related training;
- Non - peer - reviewed materials (e.g., reports, theses, or grey literature);
- Duplicates and documents not available in English.

Figure 3 summarises the screening process following PRISMA guidelines [17]. Using the four-domain query defined in Table 1, the database search retrieved 5635 records from three sources. After removal of 257 duplicates by DOI, 5379 records entered automatic screening; an abstract filter (4th domain) reduced this set to 2306 records (3073 excluded), and subsequent filters on subject area and publication year removed 22 and 469 records, respectively. Applying document-type and language criteria then excluded 128 non-article/non-conference items and 66 non-English records, leaving 1621 documents for manual screening. Title–abstract inspection discarded 992 items, resulting in 629 papers for full-text assessment, from which 524 were excluded because they did not provide substantive evidence on technology-enabled education or training in hazard-exposed critical infrastructure contexts. The final corpus comprises 105 studies included in the review (Figure 3), with full bibliographic details reported in Appendix A.

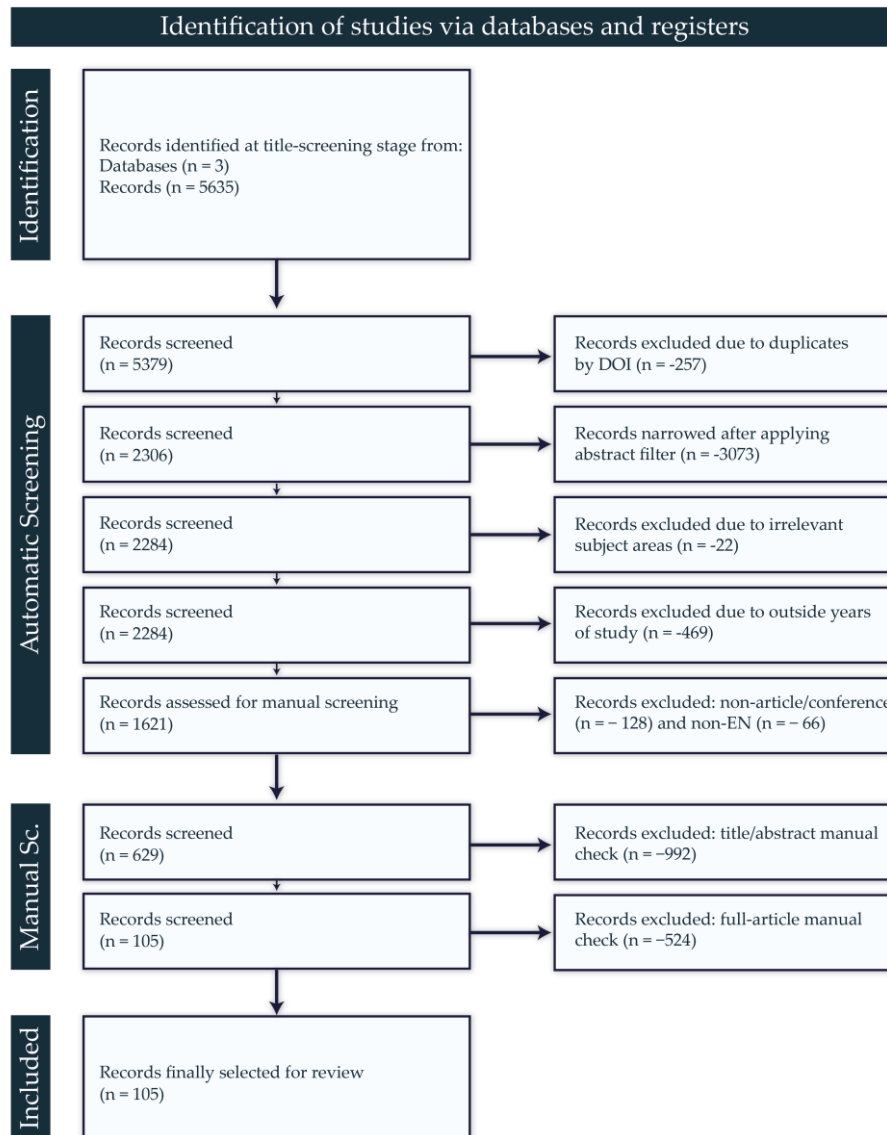


Figure 3: Overview of inclusion and exclusion criteria based on the PRISMA model

2.4. Data Extraction and Classification

Each selected study was reviewed and categorized 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);
- Infrastructure domain (e.g., transport, energy, water, health, communication);
- Stakeholders type (e.g., public authorities, industry operators, academia, civil protection);
- Hazard typology (e.g., natural, technological, cyber, or systemic);
- Implementation phase (planning, design, management, maintenance, or emergency response).

This classification enabled a cross - sectoral understanding of how educational innovation interacts with the operational and governance dimensions of CI systems and provided the foundation for the analytical framework discussed below.

2.5. Analytical Framework

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

- Descriptive analysis: mapping the frequency and distribution of studies by technology, sector, region, and hazard type;
- Thematic synthesis: identifying recurring patterns in educational approaches, instructional design, and technology adoption;
- Interpretative synthesis: connecting findings to broader discussions on digital transformation, sustainability, and resilience - oriented education.

This framework allowed both horizontal comparisons (across technologies and domains) and vertical interpretation (from empirical evidence to conceptual models), ensuring methodological rigor and conceptual depth in the synthesis of results.

2.6. Limitations

While comprehensive, this review presents several limitations that are inherent to the interdisciplinarity and linguistic complexity of the field. Despite the refinements introduced in the search strategy to filter out irrelevant uses of terms such as bridge, tunnel, or training, terminological ambiguity remains a structural limitation of research on critical infrastructures. The coexistence of engineering, educational, and computational vocabularies often generates semantic overlaps that complicate retrieval accuracy and reduce the precision of classification. Moreover, the expression critical infrastructure itself is still underused in titles and keywords, which may have resulted in the exclusion of relevant studies that nevertheless fall within this conceptual domain. As a consequence, the corpus analyzed should be regarded as representative rather than exhaustive. A further limitation concerns the rapid evolution of digital technologies, particularly Artificial Intelligence, holographic systems, and conversational agents, which may not yet be fully represented in academic literature. Publication bias toward English - language and peer - reviewed sources may also have limited the inclusion of grey or regional research.

Generative artificial intelligence (GenAI) tools, specifically OpenAI's ChatGPT, were used to support the development of this literature review. AI assistance was applied exclusively to the organization, synthesis, and comparative analysis of scholarly sources, helping to refine the academic writing style for clarity and consistency. All extracted information, interpretations, and conclusions were critically reviewed, verified, and rewritten by the authors to ensure conceptual accuracy, methodological rigor, and alignment with the research objectives. No GenAI tools were used to generate original data, figures, or experimental results, and the final content reflects the authors' independent intellectual contribution.

Overall, these limitations highlight the inherent challenges of conducting systematic reviews in interdisciplinary domains, where terminological variability and technological dynamism can affect both the breadth and depth of the retrieved evidence base.

3. DESCRIPTIVE OVERVIEW OF THE LITERATURE CORPUS

This subsection provides a descriptive and bibliometric overview of the reviewed corpus, offering a quantitative insight into the scope and dynamics of research on education and training for critical infrastructure resilience. It examines the typology of results, the chronological distribution of publications, geographical patterns of research activity, and the keywords most frequently associated with this domain. By mapping these dimensions, the analysis reveals how the field has evolved over time, where scientific contributions are concentrated, and which thematic directions are gaining prominence. The resulting overview establishes the empirical foundation for the following sections, which explore in greater depth the technological, infrastructural, and pedagogical aspects emerging from the literature.

3.1. Typology of results

The systematic literature review identified a total of 105 peer - reviewed papers from different regions of the world, highlighting diverse research strands on the application of immersive and digital technologies to critical infrastructure resilience and risk management. The research spans various subject areas, with Engineering, Computer Science and Social Sciences comprising significant portions of the literature. This interdisciplinary approach underscores the complex nature of natural hazard management and the diverse perspectives required for practical solutions.

3.2. Year distribution

Figure 5 illustrates the annual distribution of publications between 2015 and 2025. The line reports the total number of publications, while the stacked bars indicate, for each year, the relative contribution of journal articles and conference papers. Overall, the data reveal a progressive increase in research output over the period, with a pronounced rise from 2022 onwards, signalling growing scholarly interest in immersive technologies and their application to critical infrastructure resilience and hazard preparedness. The marked downturn observed between 2019 and 2021 may plausibly be linked to the disruptions caused by the COVID-19 pandemic, such as the cancellation or postponement of conferences and delays in publication and review processes.

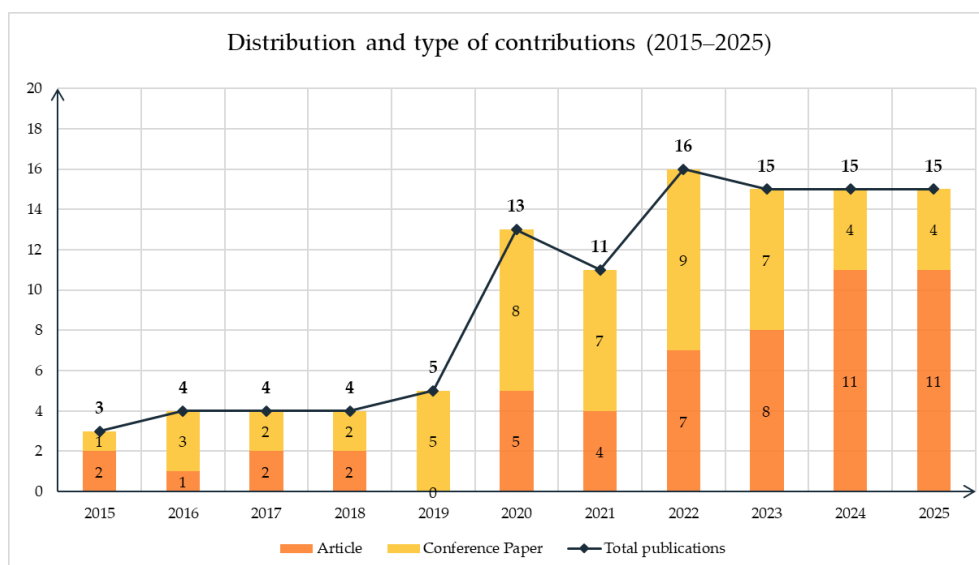


Figure 4: Documents by year. (Image created by the authors)

3.3. Geographical perspectives

The geographical distribution of the reviewed studies highlights three countries, China, the United States, and Italy, as the most active research poles in immersive learning for risk and resilience. Together, they account for nearly half of the analyzed corpus, confirming that research activity remains spatially clustered around a few key centers where technological capacity, institutional priorities, and hazard exposure intersect.

China leads this group, showing the highest concentration of studies focused on seismic, fire, and industrial hazards [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35]. 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 [23, 36, 37, 38, 39, 40, 41, 42, 43, 44, 46, 47, 48, 49, 50, 51]. 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 [52, 53, 54, 55, 56, 57, 58, 59, 60, 61]. Systems such as *BE-S²ECUR*e [53] and *VRescue* [52] 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.

Overall, the corpus highlights how immersive training for critical infrastructures has developed through geographically distinct trajectories: hazard-driven experimentation in the Asia-Pacific region; multi-hazard and institutional integration in Southern Europe; increasing cross-regional convergence through industrial digitalization and human-factor approaches in Northern Europe; and data-driven pedagogy in North America. Despite these differences, a growing cross-regional convergence is evident in the shared ambition to embed resilience education within broader technological and institutional ecosystems.

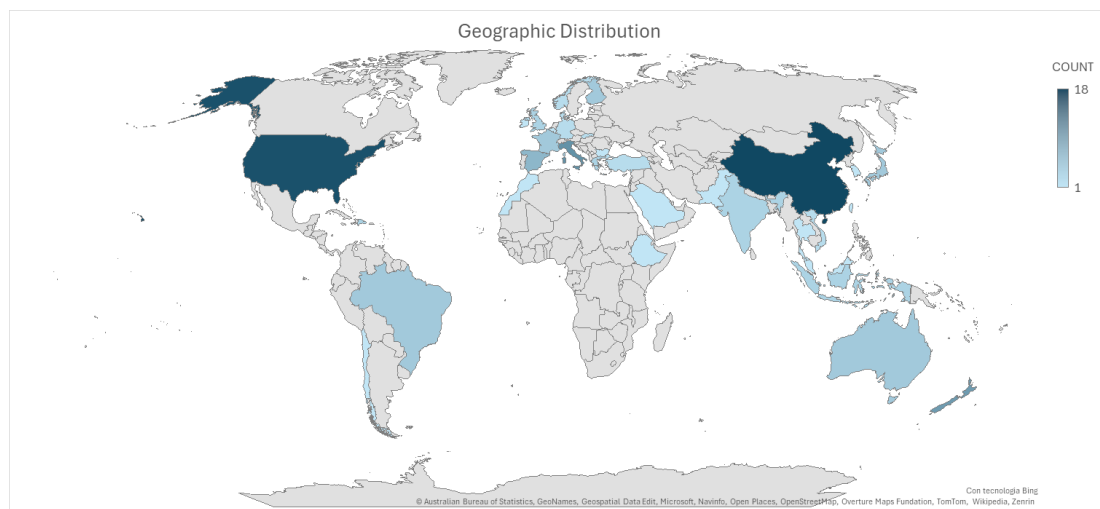


Figure 5: Geographic distribution of the reviewed studies. (Image created by the authors).

3.4. Keywords

The selected publications were further examined through a Social Network Analysis (SNA) of keyword co-occurrences to identify major thematic clusters and research interconnections. Figure 7 presents the resulting SNA visualization, which maps the relationships among keywords and highlights the density of co-occurring terms. This visual representation facilitates the identification of dominant themes and emerging subtopics within the field, providing a structured overview of how research on educational technologies and critical infrastructure resilience has evolved. It also supports the organization of the reviewed literature into cohesive thematic strands, guiding the subsequent stages of the systematic analysis and enabling a comprehensive assessment of current research trajectories.

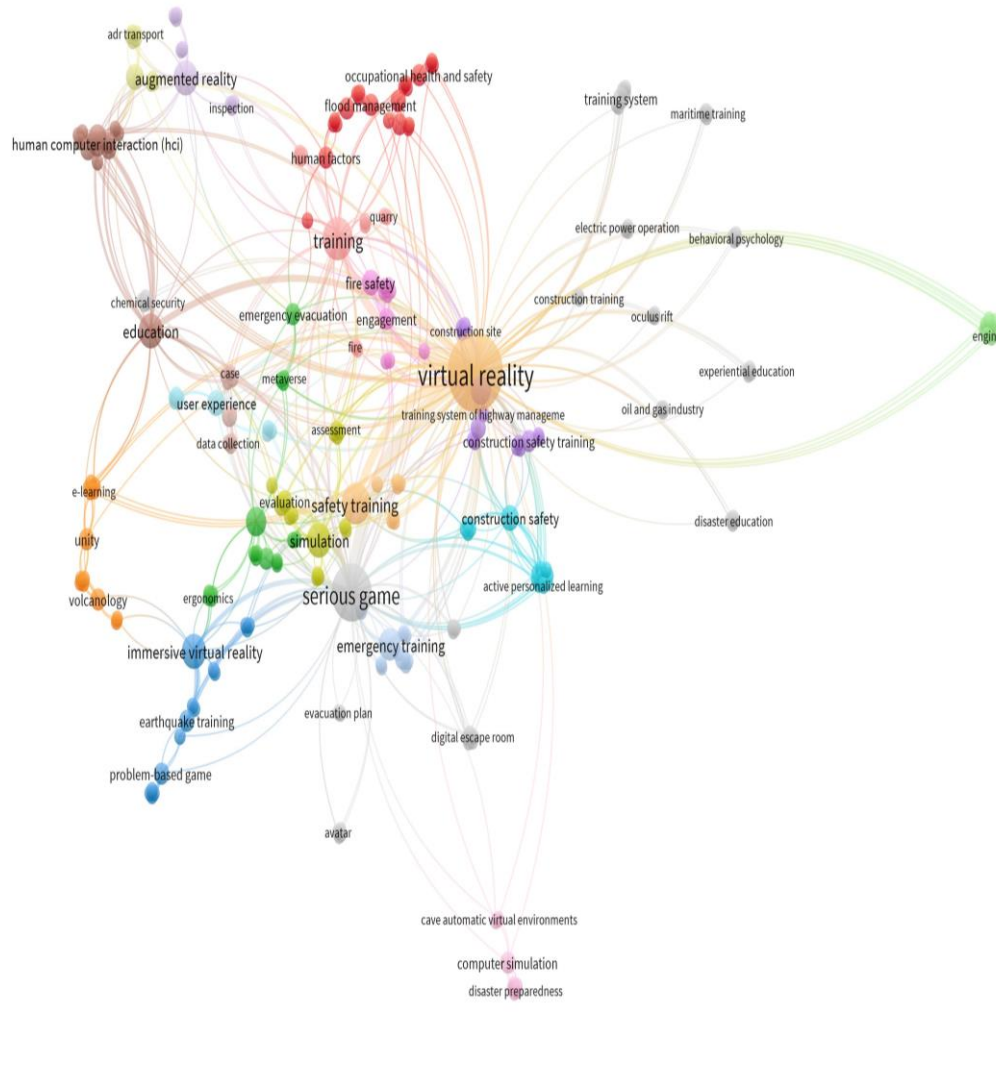


Figure 6: SNA of keyword co-occurrence in the selected papers. (Image created by the authors using VOSviewer)

4. RESULTS

This section presents a critical synthesis of the reviewed studies, organized according to the six analytical dimensions introduced in the methodological framework. The multidimensional classification provides a structured basis for comparing diverse experiences, identifying technological and pedagogical patterns across regions and time periods, and mapping how emerging educational technologies are transforming the discourse on critical infrastructure resilience and training innovation.

4.1. Technological approaches

Training for the critical infrastructure management workforce increasingly relies on advanced learning technologies that combine immersion, interactivity, and adaptability. These systems enable experiential learning and feedback-driven practice, replicating the operational and cognitive complexity of real infrastructures and allowing both professionals and non-specialists to acquire technical, procedural, and behavioral competencies in safe yet realistic environments.

To compare heterogeneous experiences within the corpus, all reviewed applications were analyzed along two orthogonal technological dimensions.

- The Interaction Layer describes how users experience and operate within the system, ranging from non-immersive desktop- and web-based applications to fully immersive VR setups, mobile AR, and mixed - reality environments, up to multi-user metaverse platforms.
- The Simulation Engine Layer defines the computational logic and data back-bone driving system behavior, encompassing knowledge-based ontologies, Building Information Modeling, Digital Twins, Artificial Intelligence, Agent - Based Systems, Internet of Things integration.

Together, these layers delineate a continuum of technological sophistication: from analytical, model-driven desktop simulations to adaptive, data - enriched, and collaborative XR ecosystems, capable of embedding human learning within digital representations of operational infrastructures. Building on this framework, the following subsections examine the main interaction and simulation configurations identified across the reviewed corpus, highlighting how technological complexity aligns with educational intent and learning outcomes.

4.1.1. Interaction Layer

This section examines the reviewed studies according to their level of immersion and the interaction modalities between users and digital environments. Each degree of immersion determines the intensity of user engagement, the sensory and cognitive load, and ultimately the depth of experiential learning achieved. As illustrated in Figure 8, the interaction continuum ranges from non-immersive desktop solutions to fully immersive, and collaborative metaverse configurations.

The concept of the reality-virtuality continuum, originally introduced by Milgram [62], defines this progression, encompassing immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), 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.

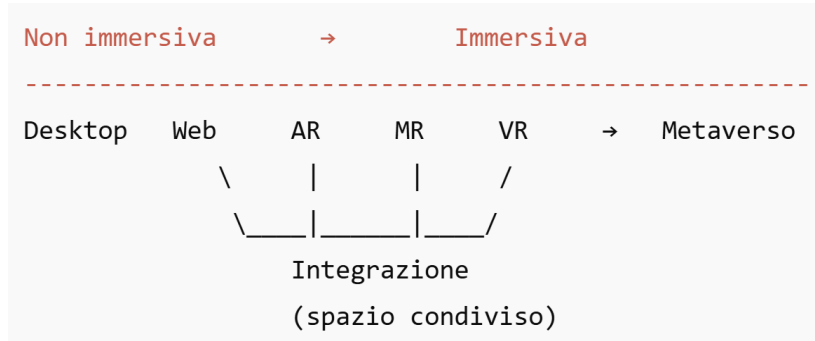


Figure 7: Reality–virtuality continuum

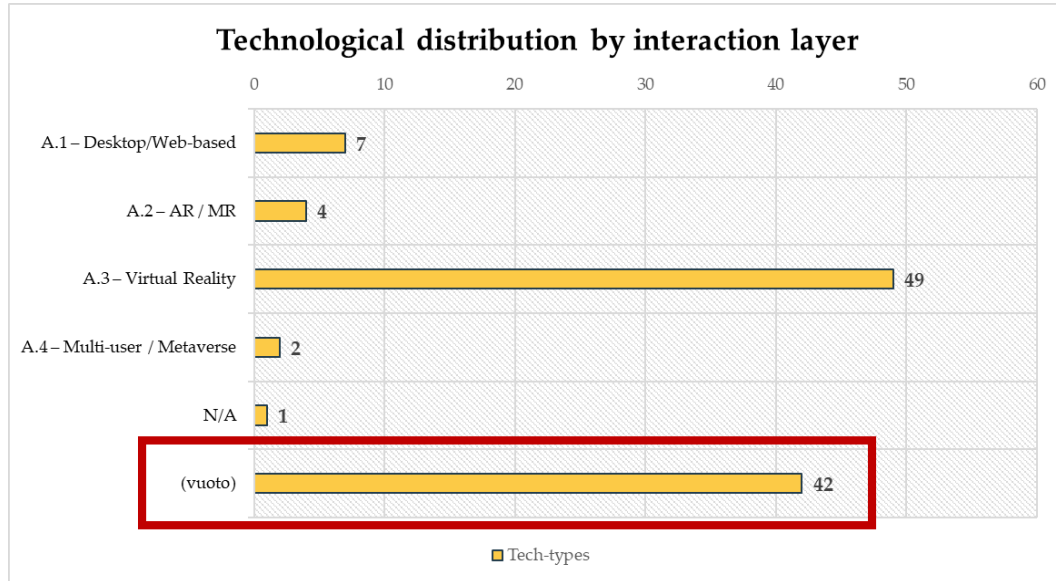


Figure 8: Distribution of technologies across the reviewed studies, classified by interaction layer. (Image created by the authors).

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4.1.1.1 Desktop and web-based

At the lowest level of the interaction spectrum, desktop- and web-based simulations represent the non-immersive analytical core of technology-enhanced learning for critical infrastructures. These systems deliver interactive 2D or 3D environments accessible through standard computers or web browsers, focusing on strategic decision-making, organizational coordination, and procedural rehearsal rather than physical embodiment. Their interfaces privilege clarity and accessibility over sensory richness, emphasizing how users interpret and control dynamic processes.

Desktop-based systems offer 3D visualization and interactive interfaces within a local computing environment, often employing dedicated rendering engines for high spatial accuracy and graphical fidelity. Among early applications Tian et al. [19] developed the Virtual City Earthquake Simulation Platform, a multi - module desktop environment that integrates 3D urban models (e.g. buildings, bridges, terrain, and street furniture) rendered with 3ds Max and V - Ray. Users can navigate the scene, trigger seismic events, and observe cascading effects such as fires, landslides, and infrastructure disruption. Interaction occurs via mouse and keyboard through an intuitive GUI, allowing the adjustment of parameters such as earthquake magnitude or evacuation routes. This system enables analytical engagement: observation, measurement, and interpretation of simulated impacts, making it suitable for planners and engineers involved in territorial risk assessment. Similarly, Nilsen et al. [18] present a 2D desk-top-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. [63] 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. [64] developed a hydropower - plant training platform where a control - room interface supports diagnostic and anomaly management tasks. The GUIDE2FR platform [65] 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. [66] propose a “dual hackathon” for flood event management, which integrates physical field exercises with a non-immersive digital support layer based on screens, drone video feeds, and shared information panels. Here too, the goal is not to recreate a substitutive virtual environment, but rather to amplify the collective readability of the situation through visual interfaces that can be accessed from standard workstations.

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. [67], which developed the Web - Based Tabletop Earthquake Exercise System. The platform operates at 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 with the system by defining resource allocations, selecting emergency response options, and assessing outcomes directly on shared maps. This multi-user interface reproduces the structure of real command chains, where different institutional roles coordinate through information dashboards and simulation playback. The system’s browser - based accessibility facilitates large - scale participation and cross - agency training, extending traditional tabletop exercises into interactive, data - driven environments. Instead of individual immersion, the focus lies on collaborative situational awareness and the ability to interpret, communicate, and act upon visualized information in real time. This mode of interaction reflects the logic of collective simulation, where users experience the model through decision coordination rather than sensory engagement. A closely related example is the Virtual Safety World developed by Shiradkar et al. [48], a multi-user 3D platform accessible from standard PCs that, in the context of fire - safety and evacuation training, compares a traditional slide - based safety training (SBST) with a first-person navigable “virtual world”. Although it remains fully non - immersive from a sensory standpoint, the system introduces avatars, interactive objects, and situated tasks, encouraging participants to rehearse procedures within a shared digital environment rather than merely observing static content.

Across these non-immersive, multi-user platforms, a recurring configuration emerges: a browser - or desktop-based delivery model, shared access to the same scenario, and a clear separation between simulation logic and the visual and interaction layer. The same pattern recurs in other desktop and web systems within the broader natural - hazard corpus. Building on these interface principles, several desktop and web-based systems maintain a distinction between a simulation core and a thin, configurable GUI layer. In the construction domain, the virtual construction safety framework proposed in [68] further exemplifies this approach, modelling 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 re-configured without modifying the underlying models [40, 69, 70]. 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. Visualisation 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 [41, 25]. 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 [71, 72]. 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 [41, 37, 73]. From an engine perspective, this preserves a clean architecture: the model computes state transitions, while a rule manager interprets them into feedback (scores, status colours, end - of - round re-ports) [74, 25]. The hazard domain changes across cases, but the pattern is stable: non - immersive systems are engineered as configurable, low - friction shells around a model, optimised for repeated use, batch comparison of scenarios and easy integration into classroom or workshop routines.

Overall, the desktop and web-based stratum of the interaction spectrum offers a non-immersive, GUI-centred mode of engagement oriented toward operational clarity, replicability, and shared control of scenarios and, as comparative evaluations suggest, can approach the cognitive effectiveness of more sophisticated XR configurations while maintaining minimal hardware requirements.

4.1.1.2 Augmented Reality - Mixed Reality

Intermediate levels of immersion are represented by Augmented Reality and Mixed Reality, which bridge the physical and digital dimensions of learning. Unlike fully immersive VR environments that detach users from their surroundings, AR and MR systems superimpose digital information onto real-world settings, creating hybrid experiences that preserve physical context while enriching it with interactive data. This duality makes them particularly effective for maintenance, inspection, and operational training, where spatial awareness and physical manipulation remain essential.

The reviewed literature reports several experimental applications of AR and MR technologies, often using *Microsoft HoloLens* or handheld mobile devices as interaction platforms [75, 24, 34, 76, 77, 27]. These systems merge hands-on practice with contextual visualization, allowing trainees to follow step-by-step procedures while maintaining full perception of the physical environment. Across the corpus, a coherent model of on-the-job procedural support emerges, in which digital overlays structure real-world action rather than simulate alternative environments.

Typical configurations include mobile AR modules coupled with 3D viewers for fire-rescue manoeuvres [24], or pre-flight inspection systems that convert checklists and manuals into multimedia content anchored to aircraft components [27]. 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.

Similar principles are applied in industrial and transport infrastructures, where AR overlays provide real-time guidance, hazard alerts, and diagnostics. MR interfaces extend these capabilities by synchronizing virtual annotations with physical components, supporting collaborative troubleshooting and remote supervision. Advanced MR systems focus less on immersion and more on precise spatial registration between digital and real elements, enabling coordination across multiple roles in complex scenarios. The *FightARs* platform [77] 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 [34] 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 [76] 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 [75].

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 [78, 79, 80]. 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 [43, 45]. MR headsets contribute spatial mapping directly on-device, ensuring that holograms remain anchored to real-world geometry [77, 34]. 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 [56].

Beyond individual use, co-present MR sessions enable multiple participants to view and manipulate the same spatially anchored content from different perspectives. Results consistently show that, while imposing a lower sensory load than VR, AR and MR configurations enhance situational awareness, self-efficacy, and procedural fluency by combining digital augmentation with physical context.

These hybrid approaches effectively reduce operational risk and improve the transfer of emergency strategies from simulation to real-world practice. By merging the sensory immediacy of physical environments with the scalability of digital overlays, AR and MR applications provide a foundation for collaborative learning scenarios and represent an intermediate step toward more fully immersive, multi-user metaverse ecosystems.

4.1.1.3 Virtual Reality

Among all the technologies examined, VR emerges as the most mature [81] and widely implemented modality in the analysed corpus. VR systems extend the concept of immersion by allowing users to interact with three-dimensional digital environments from a first-person perspective, combining visual, auditory, and kinesthetic feedback in ways that range from screen-based navigation to fully enveloping experiences. This flexibility makes VR particularly suited for reproducing complex and hazardous situations in CI, such as fires, tunnel incidents, plant failures, or urban evacuations, where direct physical training would be impractical or unsafe.

The reviewed applications encompass both gamified systems for behavioral and procedural training and non-game-oriented configurations, such as semi-immersive theatres and replay simulators, where the emphasis shifts toward observation, debriefing, and analytical reflection. Collectively, these approaches integrate visualisation, simulation, and interaction to support learning through action and reflection.

The following sections describe how these systems materialise across different levels of immersion; (i) non-immersive, (ii) semi-immersive, and (iii) fully immersive, each supported by specific device configurations and interaction modes. In addition, some studies propose hybrid arrangements, in which the same content can be accessed either in desktop mode or via HMDs, allowing adaptation to available resources and to the specific type of exercise.

Non immersive systems

Non-immersive VR applications are generally implemented in desktop mode, with 3D scenes displayed on standard monitors or large projection screens. These configurations, characterised by low physical engagement but high accessibility and scalability, are well suited for classroom use, rapid training iterations, and contexts in which hardware resources are limited. Interaction typically occurs through conventional input devices (mouse, keyboard, joystick) while still allowing users to explore three-dimensional environments, often encapsulated in simplified serious games. Despite the absence of sensory immersion, such systems have proven effective for training procedural reasoning, hazard identification, and decision-making under time constraints [61]. 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 optimised 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 prioritise scenario configuration and results interpretation while the engine manages geometric and physical computations [69, 70, 40, 41, 37, 82, 59, 83]. 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 [84] or in professional contexts such as firefighter training, exemplified by the *Fireman Rescue* simulation [85], emergency robot rescue training systems [22], and railway level-crossing safety applications [86]. Other examples include emergency preparedness scenarios based on large-scale virtual environments, such as the simulation of a terrorist attack in a train station [61], 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 [87, 47]. Examples include the *Second Life*-based 3D platform for university evacuation training [87] and the *Megacity CVE* environment, which provides a non-immersive version for PC-based evacuation exercises [47]. Cross-platform implementations expand these capabilities, maintaining desktop clients as default access points for urban-risk training [88; 89; 90; 91; 92; 30], or providing alternative interfaces for PCs and large-format displays [56; 49]. Across all these variants, non-immersive systems share a consistent architecture: 3D scenarios rendered on screens, standard input devices, and game or assessment logic handled through graphical interfaces, an approach that maximises accessibility, repeatability, and dissemination without imposing heavy technical requirements.

Semi - immersive systems

Semi-immersive configurations occupy an intermediate position between purely screen-based use and fully immersive VR systems. They exploit large-scale projections or enveloping displays to enhance the sense of spatial presence while maintaining physical co-presence among participants. In these environments, users share a collective field of view rather than wearing individual head-mounted displays (HMDs). Physical props and differentiated roles are often integrated, transforming the training space into a common scene for discussion, coordination, and decision-making.

Cylindrical or panoramic theatres equipped with multiple projectors exemplify this approach, immersing trainees in simulated emergency environments such as underground mining scenarios where rescue teams operate within a continuous visual field controlled by an instructor [93]. These systems foster shared situational awareness and teamwork, while a corresponding desktop VR version of the same content enables direct comparison between the two modalities. The cylindrical room enhances visual engagement and co-presence, whereas the desktop configuration reduces costs, motion sickness, and logistical constraints, making it more suitable for frequent training cycles and large audiences [93].

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 [51]. 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.

The same principle extends to CAVE (Cave Automatic Virtual Environment) systems, which project stereoscopic imagery on multiple walls to achieve high spatial awareness and collaborative immersion. In these room-scale configurations, participants can move freely within the physical space, making them suitable for behavioral studies and coordination exercises. This configuration has been adopted in various domains. As shown in Figure 10, one such implementation employs a hexagonal five-wall CAVE with continuous high-resolution projection and high-precision tracking of both participants and physical props, such as fire extinguishers, enabling realistic school fire preparedness training simulations [94].



Figure 1. Overview of the hexagonal CAVE VR environment.



Figure 2. Indoor fire simulation in the CAVE environment.

Figure 9: Example of CAVE-based application

In open-pit mining, Unity-based simulations reproduce quarry topography, elevation changes, and ambient soundscapes while logging individual and group performance [59]. 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 [95].

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 [96]. 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 [97].

Semi-immersive systems therefore complement rather than compete with fully embodied VR. They offer many perceptual and collaborative benefits of immersion without the sensory load or cybersickness associated with HMDs. Within the interaction continuum, these systems bridge single-station simulations and headset-based environments, offering a controlled and ergonomically sustainable framework for guided observation, collaborative decision-making, and the development of shared understanding, an approach that anticipates several of the multi-user and metaverse logics discussed later.

Fully immersive systems

Within the spectrum of interaction levels, fully immersive VR represents the configuration that most distinctly separates the user from the physical world. When wearing a head-mounted display, the real environment is replaced by a stereoscopically rendered virtual space, updated in real time according to head and hand movements. Six-degree-of-freedom (6DoF) tracking combined with controllers or hand-tracking systems enables first-person exploration, object manipulation, and interaction with diegetic interfaces, producing the experience of being *inside* the simulated environment rather than observing it externally. 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 [98, 99, 36]. 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 [100; 101; 37]. 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* [20, 21, 26, 31, 32, 35, 52, 55, 57, 58, 60, 102, 103, 104, 105, 106, 107, 108] or *Oculus Rift* [26, 106, 58, 47, 28, 109, 110, 111, 112, 113], 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 [31].

Standalone headsets, such as the *Oculus Quest* [114, 33, 50, 115, 116, 54, 42] and the *Meta Quest 2* [117, 118, 53, 113, 55], 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 [115; 94]. Their versatility also makes them suitable for field-oriented or multi-hazard applications requiring mobility and minimal logistical constraints [42, 53].

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 [119, 120, 121, 122], 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 [30, 57, 58, 87]. 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 [87].

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 [30]. 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 [57, 58]. 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 [95].

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 [60]. Through the integration of auditory, haptic, and motion feedback, these systems achieve multisensory congruence that strengthens spatial presence, situational awareness, and behavioral learning under realistic stress conditions.

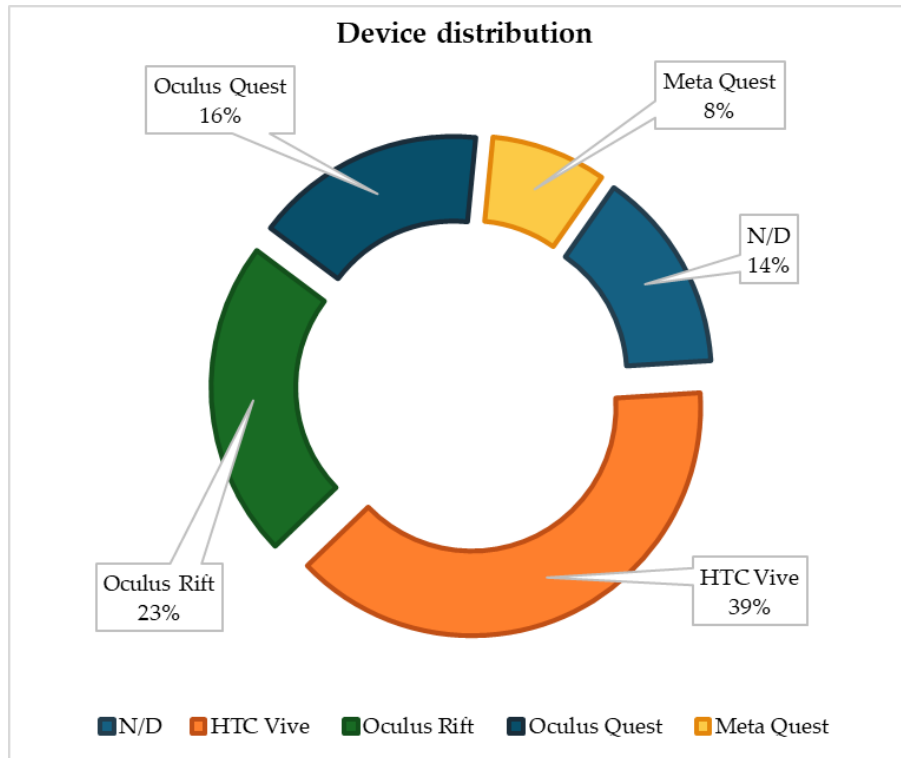


Figure 10: Distribution of devices in fully immersive VR studies with totally virtual environments. (Image created by the authors).

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 [30, 57, 58, 95, 107, 111, 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 practising coordination, victim search, and hazard mitigation [52, 57, 58].

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 [25, 36, 73, 69, 70, 40]. In the context of technological and NaTech risks, fully immersive environments reproduce industrial plants, refineries, and energy facilities to visualise 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 [30, 42, 60].

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 [31, 60, 109]. Educational and reflective applications [54, 112, 113] 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.

4.1.1.4 Multi User/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 visualise 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 [123]. 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 [39, 124, 125]. 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, 66]. 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 [126]. 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 [23].

In the context of emergency response, multi-user VR configurations also support collective practice in high-risk environments. The *VRescue* platform [52] exemplifies this approach, enabling simultaneous participation of rescuers and instructors within a photogrammetric reconstruction of a collapsed city. Similarly, the HCP–VR system [55] 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.

Collectively, multi-user and metaverse systems mark a paradigm shift from individual experiential learning to collective simulation, where knowledge is constructed through collaboration, negotiation, and shared awareness rather than isolated performance.

4.1.2. Simulation Engine Layer

The simulation backbone underlying each reviewed application reveals the evolution of learning technologies for critical infrastructure training, from early rule- based frameworks to more complex data-driven, adaptive, and cyber-physical systems.

Over time, the corpus reveals a clear progression: initial studies primarily codified emergency procedures through logical scripts, ontologies, and fixed rule sets, while more recent contributions integrate spatial data models, agent-based dynamics, and real-time information flows. This evolution progressively narrows the gap between training simulations and operational environments, transforming VR and XR systems from static demonstrators into dynamic platforms capable of reproducing behavioral, environmental, and infrastructural feedback in real time.

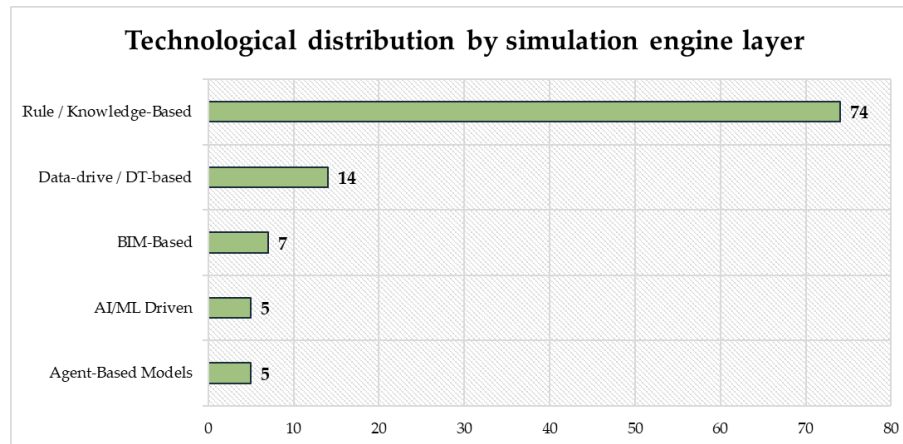


Figure 11: Technological distribution of the reviewed applications by simulation engine layer.
Image created by the authors.

4.1.2.1 Rule and Knowledge-Based Systems

The earliest generation of simulation environments in the corpus is characterized by rule- and knowledge-based architectures, where procedural knowledge and emergency actions are formalized through explicit scenario logic. These systems encode decision pathways as sets of predefined rules or ontological relationships, translating expert knowledge into structured models that can be replayed, audited, and validated.

Among the first examples of this category is a virtual simulation of a terror attack in a train station [61], which applies a clear sequence of rules to connect user actions with safety recommendations. Each action or mistake produces a corresponding reaction, such as feedback messages, warnings, or corrective instructions. The experience is entirely governed by predefined if–then relations that regulate what happens when the player encounters smoke, debris, or fire. In this way, the simulation works as a chain of cause-and-effect episodes that reproduce the logic of procedural training, forming one of the earliest demonstrations of a knowledge-based simulation engine.

Another notable instance of this approach is the *Web-Based Tabletop Earthquake Exercise System* [67], which operates at the territorial scale. The platform applies hierarchical logic to model decision chains across provincial, municipal, and county authorities: each user's choice, resource allocation, communication flow, or intervention timing, triggers algorithms that propagate consequences through the simulated administrative network. The resulting architecture mirrors real command hierarchies, transforming decision-making into a process of strategic reasoning rather than an immersive sensory experience.

In more recent literature, analogous rule- and knowledge-based logics are adopted across numerous application domains, where simulators and serious games translate technical standards, 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 [22, 31, 89, 109, 117, 120]. 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 [59, 93]. 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 [75, 118], 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 [26, 30, 92, 114, 122, 126]. Related studies extend the same principle to fire safety and evacuation training [20, 77, 85, 91, 102, 110, 115, 119], construction safety [32, 33, 83, 88], healthcare and emergency preparedness [46, 106], aircraft emergency procedures [90], photovoltaic and power-plant systems [29, 64, 96], and XR training for confined spaces [56, 60], showing that rule- and knowledge-based logics remain central to the modelling 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 [86].

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 [112], to vary resource availability and avatar roles in motivational experiments [18, 57, 58], and to guide teacher and student responses during school evacuation drills [21, 48, 76, 84, 94, 97, 116]. The same logic governs mission flow and scoring in professional rescue simulations such as *VRRescue* [52]. More recent developments reformulate this rule-based structure into adaptive frameworks, such as the “spiral narrative” introduced in [113], where feedback loops and scenario restarts support reflection-in-action and incremental learning.

Across these implementations, rule-based systems have evolved from static scenario sequencing to dynamic narrative frameworks capable of blending behavioral control with pedagogical adaptability. Hazard-oriented applications continue to rely on similar logic, encoding mission steps, scoring rules, and error conditions as finite-state machines or runtime rule tables [41, 37, 73]. Instead of simulating behavior from the bottom up, these engines apply *if–then* relationships to discrete events, guaranteeing predictable scenario flow and facilitating validation when training must comply with formal safety or operational protocols.

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 [74, 38, 121]. 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 [104], on evacuation times and routes [87], on risk scenarios in urban construction sites [51], on checklists for pre-flight safety inspection [27], on the construction sequence of wind towers modelled through mathematical procedural animation [50], on risk and emergency response procedures tested in a hackathon focusing on real flood scenarios [66], on safety pathways grounded in hazard recognition [49], and on simulated operations in gas power plants that follow codified EPR/HSE logics [103]. 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 implementations, such as *HCP–VR* [55], apply the same principle through dual guided and evaluated modes, where encoded procedural rules drive feedback, error detection, and task sequencing in high-capacity pumping operations for civil protection training, demonstrating how traditional rule-based logic can be embedded within immersive procedural simulators. Technologically, this architecture maintains conceptual clarity and traceability, making it possible to directly map policy changes or revised procedures onto the corresponding logic within the training engine.

4.1.2.2 BIM-based

As simulation technologies matured, attention shifted from abstract procedural logic to spatial and architectural realism. Depending on the infrastructure typology and lifecycle stage (design phase, existing asset, or hypothetical model), different strategies can be adopted to represent geometry, materials, and semantics within immersive simulations. The integration of Building Information Models with game engines plays a central role in this evolution, particularly for existing buildings where digitization products such as 3D scans or Revit models can provide highly detailed architectural (e.g. building element material, pieces of furniture, lighting conditions and evacuation systems) and semantic representations. However, “integrating BIM” rarely means transferring the full information model: it is more often a selective curation process, where semantics are reduced to what is actionable in real time, while properties crucial for simulation (e.g., physical parameters for fire/smoke or crowd dynamics) require additional mappings or simplifications. This creates a recurring 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 [28, 96]. 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 [82]. 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 [28]. 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 [68]. 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 [32].

This approach is exemplified in the Auckland City Hospital studies [95, 111], 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 [107], 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).

In this context, BIM is not merely a geometric reference but a semantic data backbone – yet in many of the reviewed cases this “backbone” is effectively a minimal, fit-for-purpose semantics (IDs, categories, a small set of properties) that enables scripting, while richer BIM semantics are either discarded or manually reconstructed to become operational in real time. The consequence is that the apparent informational completeness of BIM can mask strong assumptions about what truly matters for training and about which phenomena (fire/smoke, human behavior, operational dynamics) are actually being modeled. This integration demonstrates how architectural accuracy and procedural fidelity can coexist, transforming digital building models into interactive training infrastructures. 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 [68]), the more it becomes sensitive to data quality and governance. Conversely, highly operational pipelines such as the tunnel workflow [28] 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. Despite the broad consensus on the pedagogical value of BIM–VR integration, several technical

challenges persist. BIM datasets often contain large volumes of information and may lose material attributes or textures during conversion to real-time engines. To maintain usability, most studies highlight that training-oriented BIM models do not require engineering-level detail but must ensure perceptual credibility and behavioral validity. Balancing computational efficiency with visual realism remains one of the key frontiers in developing immersive digital-twin environments for education and operational resilience.

In parallel, BIM-based engines provide a structured way to reuse design - time information in interactive training. Pipelines that export Revit or IFC models to game engines perform a sequence of transformations: mesh decimation, collider generation, occlusion setup and material substitution [28]. 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. This creates new opportunities for scenario scripting: all emergency exits, extinguishers, or signage elements can be queried and manipulated collectively, or compliance between planned and simulated wayfinding can be dynamically verified. Technologically, this approach transforms BIM from a static repository into a living database that immersive engines can interrogate and adapt for training – yet such “liveness” is not automatic: it depends on verifiable pipelines, update rules, and validation metrics. Without governance (BIM versioning, export consistency, controlled attribute loss), the system risks producing a twin that is visually credible but semantically impoverished, where procedures are correct “in the engine” more than in the real world.

4.1.2.3 Agent-Based Models

A further conceptual leap in simulation design is represented by agent-based modelling, which introduces collective behavior and crowd dynamics into immersive training environments. This paradigm shifts the focus from individual procedural actions to the emergent properties of many autonomous entities interacting under shared environmental constraints.

Within the corpus, this approach is exemplified by the *BE-S2ECURE* platform [53], which integrates physical hazard models such as earthquake and heatwave dynamics with agent-based simulations of human evacuation. By coupling environmental and behavioral layers, the system evaluates how spatial configuration, exposure, and human response jointly influence resilience performance. In educational terms, agent-based simulation bridges the gap between architectural design and behavioral science, enabling participants to understand how environmental structures affect collective outcomes and emergency decision-making.

A second notable example is provided by the study Sharma et al. [47], which adopts an explicit Agent-Based Modeling and Simulation (ABMS) engine for evacuation in virtual reality. In this case, overall crowd dynamics emerge from the interaction of multiple autonomous entities – avatars and computer-controlled agents assigned hostile, non-hostile, leader-following, selfish, or goal-following roles – governed by local decision rules, multi-level crowd-behaviour strategies (ViCrowd: rule-based/reactive and group-based), and waypoint algorithms that drive movement towards evacuation goals rather than predefined procedural scripts.

Complementing object-centred approaches like BIM, agent-based engines model behaviour through sets of local rules applied to autonomous entities. Each agent perceives its surroundings, reacts to stimuli, and interacts with other agents based on probabilistic or heuristic rules. In participatory flood-simulation environments, a dedicated agent-based module governs individual responses while a hydrodynamic component calculates water movement and environmental change [124, 39, 125]. The overall architecture is typically organised into three layers: the spatial substrate, the behaviour rules and the human interface. Facilitators and participants interact primarily with configuration parameters, while the simulation engine manages agent evolution and aggregates outcomes for analysis or debriefing.

This modular design is technologically advantageous because it allows the same behavioral core to support both training and analytical experimentation. Changing the interface or logging strategy converts the platform from a participatory educational tool into a quantitative model for scenario testing. By linking individual decision-making to collective behavior, agent-based systems thus enable the exploration of cascading effects, coordination challenges, and resilience strategies within complex, dynamic infrastructures.

4.1.2.4 AI and ML Driven Systems

Parallel to the emergence of rule-based and agent-based approaches, a new generation of serious games introduces artificial intelligence (AI) and machine learning (ML) to personalize the training experience and enhance system adaptability. AI-driven adaptation enables the simulation engine to continuously assess user performance, adjusting parameters such as task difficulty, feedback frequency, and pacing to maintain engagement and prevent cognitive overload.

This principle is implemented in the Adaptive Serious Game for Emergency Evacuation [54], 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 [42], 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.

Together, these systems mark a transition from fixed scripting to machine-guided learning, in which the simulation responds to the trainee's evolving skillset and situational awareness. Instead of predefined sequences, the experience becomes a dialogue between user and algorithm, driven by data and behavioral feedback loops.

Further along the data-driven spectrum, AI and ML components appear as embedded services inside some engines rather than as visible features. Flood-susceptibility tools, for instance, train classifiers on spatial predictors and then ship the trained model as a callable module; the viewer requests susceptibility values at runtime and displays them as colour fields or height maps. Similarly, adaptive-training platforms log user actions and derive difficulty adjustments or pacing decisions through learned mappings, without changing the art assets or scene graphs [32, 121]. From an engineering perspective, these ML components function as black-box models with defined input–output contracts, simplifying integration but raising questions of explainability when transparency is essential to the learning process.

At the opposite end of this spectrum, some systems employ AI/ML models as the actual decision-making core of the training engine. On the one hand, in the context of evacuating educational buildings in a metaverse environment, a guidance agent trained via Deep Reinforcement Learning (rainbow DQN) is deployed on top of a social force model, transforming the state of the environment into discrete actions on dynamic guidance signs with the goal of minimizing overall evacuation time [23]. On the other hand, in fire-rescue skills training, artificial intelligence is implemented as a hybrid optimization and risk-assessment pipeline, in which Particle Swarm Optimization algorithms compute intervention paths based on an explicit fitness function, and a data-driven risk assessment framework – combining fuzzy comprehensive evaluation, Monte Carlo simulation, AHP, and Bayesian networks – dynamically updates risk indices from historical data and training logs [24]. Conceptually, the former exemplifies a model-free policy learning approach for controlling evacuation strategies, whereas the latter represents a model-based setup in which optimization and probabilistic inference are tightly integrated into the rescue training scenario.

The integration of AI and ML within training simulations thus reflects an ongoing convergence between data analytics and pedagogy. By combining predictive modelling with behavioral adaptation, these systems move toward continuous, evidence-based learning cycles that align simulation complexity with user competence and operational goals.

4.1.2.5 Data Driven and Digital Twin Systems

The most recent and technologically advanced simulation environments are built on data-driven and digital-twin architectures, where training and operation progressively converge. In these systems, simulation engines are dynamically linked to structured datasets, sensor inputs, or analytic modules, creating adaptive learning environments that mirror the logic of real infrastructures.

The Virtual City Earthquake Simulation Platform [19] represents an early precursor of this approach. Its multi-module architecture integrates 3D urban data, hazard parameters, and interdependent infrastructure networks, enabling comparative analysis of seismic impacts and cascading failures. This modular design anticipates the principles of digital twins, where each component of the city (terrain, buildings, and lifeline systems) can be parameterized and recombined for different training and analytical purposes.

Following the same trajectory, integrated XR–DT frameworks such as *GUIDE2FR* [65] unify digital-twin representations with IoT sensing and live video feeds, augmented by machine-learning modules that forecast environmental variables. *GUIDE2FR* operationalizes this coupling through a geolocated, web-delivered building twin continuously updated from heterogeneous sensing, where threshold-based semantic layers and dashboards expose the live state of the facility and support situational interpretation. A multistep ML forecasting layer predicts selected environmental indicators from drill data, enabling predictive monitoring rather than static visualization [65]. 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 [26, 75]. These applications connect BIM, GIS, and IoT data streams to support immersive maintenance rehearsal, safety training, and predictive asset management, thereby linking operational analytics with human performance. A closely related DT pattern is reported for safety training in automated production environments, where real-time synchronization merges machine/cell telemetry with human indoor positioning into the VR runtime via robotics middleware and VR clients, enabling live testing of safety zones and stop conditions [105].

A parallel development can be observed in the locomotive crew VR training environment proposed by Gao et al. [35], which merges CAD-based mechanical modelling with Unity3D simulation engines to create an interactive, data-driven learning twin. The platform links real-time operational fault diagnostics with immersive instruction and automated assessment, illustrating how digital-twin logic extends from industrial operations to vocational training contexts. In the same line, the EGCERSIS simulation engine [108] couples a digital twin of a metro station with a decision-support core capable of processing sensor data and user actions in real time, transforming crisis scenarios into adaptive, data-driven exercises that integrate immersive visualization with procedural analytics. A further data-driven training twin is achieved when real site states are re-played into the virtual environment: *VirtualSafeConDM* [68] reconstructs training scenes from as-built digital models and measured movement traces, instantiates and updates hazard/protective zones based on safety-rule geometry and observed positions, and logs zone interactions as structured incidents exportable for post-hoc behavior analytics.

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 [25]. 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 [99, 36]. 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 [121].

Data-driven logics also underpin emerging emergency-response twins, where photogrammetric reconstructions and AI-assisted routing transform virtual environments into operational proxies. In rescue-training systems such as *VRescue* [52] and *VRescuer* [42], immersive simulations are linked to performance data, route optimization, and environmental variability, enabling continuous feedback and analytics-based decision support. DT-oriented derailment training frames the twin as a coupled architecture spanning the physical system, its virtual counterpart, a unified data layer, and service modules: field data are used to drive simulation and rescue-plan validation, while physics constraints and collision checks support operational decision workflows [34].

In this category, probabilistic Bayesian event-tree engines such as *BET_UNREST* are executed alongside volcanic unrest exercises to update eruption scenarios and inject structured forecasts into the training flow [71]. Similarly, tsunami inundation solvers have been coupled with school evacuation drills, generating composite scenario movies that allow experts and citizens to iteratively test and refine evacuation strategies [72].

At the architectural level, metaverse-labelled 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 [123, 56].

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 [28]. 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.

Overall, data-driven and model-integrated systems mark the transition from visual fidelity to functional intelligence in training design. By connecting information modelling, sensing, and human interaction, they enable the emergence of living digital twins, adaptive, evidence-based environments that strengthen both technical accuracy and human preparedness across the full spectrum of critical-infrastructure domains.

4.2. Pedagogical Approaches

Training for critical infrastructures goes beyond procedural repetition: it relies on pedagogical architectures capable of transforming simulation into authentic learning experiences. Across the reviewed studies, learning does not occur within virtual environments, but through them - at the intersection between technological mediation and cognitive construction. Immersive technologies and serious games reveal this common intent through a continuous process of learning through action, reflection, and adaptation. This section follows that trajectory: from experiential and situated learning, through structured, game - based frameworks, to reflective and adaptive learning ecosystems that sustain long - term competence and resilience.

4.2.1. Experiential and Context-Based Learning

At the foundation of all immersive education lies experiential learning: knowledge is built through action, perception, and situated engagement rather than abstract instruction. By placing participants in realistic operational contexts, such as hospitals, industrial facilities, or urban areas, these systems reproduce the complexity of decision - making under stress. In earthquake - related applications, for instance, Lovreglio et al.[95] and Feng et al. [111] 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 [127] 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 [98; 99; 36]. 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 [78; 79; 80; 77]. This experiential grammar combines guided exploration, embedded visual cues, and structured autonomy, bridging the gap between knowing and doing [128, 129] and building perceptual awareness, procedural fluency, and adaptive response. In training for critical infrastructures, experiential learning therefore provides the ground layer of competence: it builds perceptual awareness, procedural fluency, and the ability to respond adaptively to evolving operational conditions.

4.2.2. Serious Games as Structured Learning Environments

Building on experiential learning principles, Serious Games represent a structured pedagogical modality that integrates narrative design, feedback systems, and interactive challenge into coherent learning frameworks. Rather than serving as mere add-ons to simulation, SGs constitute self-contained learning environments that translate technological affordances into rule-based, emotionally 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) [130] to the design of an emergency-preparedness simulation in a train-station terror attack scenario [61]. 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, 20, 21, 22, 26, 28, 29, 30, 31, 32, 33, 42, 47, 49, 52, 53, 54, 57, 58, 59, 60, 61, 75, 82, 83, 84, 85, 86, 88, 89, 90, 91, 92, 94, 95, 102, 103, 104, 105, 107, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 126].

These environments combine realistic operational settings with structured objectives, feedback loops, and progression mechanics that reinforce decision-making and procedural reasoning under simulated stress. Participants navigate complex scenarios, perform critical operations, and experience the consequences of their choices, practicing evacuation strategies, hazard identification, maintenance protocols, or emergency coordination across domains ranging from education and healthcare to transport, energy, and process industries.

Through their ability to synchronize the engine layer (the logic of rules, feedback, and system behavior) with the interface layer (the domain of perception, action, and emotion) SGs embody what can be defined as a pedagogy of the virtual: a cognitive and emotional space where knowledge is enacted through interaction, experience, and reflection. This synthesis of structure and immersion positions SGs as a central mechanism for translating technological sophistication into meaningful, evidence-based learning for safety and resilience.

The pedagogical architecture proposed by Gao et al. [35] 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 is the backbone of serious - game pedagogy, providing a temporal and emotional framework for learning. Across the reviewed corpus, SGs adopt a variety of narrative structures and pedagogical mechanisms that reflect different training objectives and learner expertise.

- Linear narratives, common in early applications [95, 111, 112], 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 (53, 54, 107);
- Reflective storylines, exemplified by spiral or feedback - driven narratives, integrate reflection - in - action through iterative redo cycles [113].
- Mission - based storylines immerse participants in task - oriented operations, such as urban rescue and rescue or evacuation drills, emphasising teamwork, situational awareness, and leadership (52, 97). Structure decision episodes allow learners to observe the consequences of their choices over a small number of scenes [74, 37, 38].

These structures sustain cognitive flow [131], 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 [132], 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. [113] and Rahouti et al. [54]

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 emphasise procedural clarity [41; 37; 73]. Immediate feedback - through scores, status changes, or corrective prompts, refinement across multiple iterations [74; 101; 32]. 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

Regardless of the degree of immersion, most VR - SGs present progressive, self - contained scenarios within a storyline. In terms of interaction, users generally operate from a first-person perspective, viewing the scene through the eyes of the virtual character. This perspective is considered the most appropriate for enhancing embodiment, particularly in view of the non-immersive application, and teleportation was chosen as the movement solution. 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 [87]. Some studies [60, 106] 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 [106]. 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. The pedagogical relevance of interactivity is further supported by comparative research on emergency-preparedness simulations [61], which contrasted interactive and non-interactive versions of the same scenario. This investigation demonstrated that active participation produced higher emotional arousal, perceived threat, and self-efficacy, key variables of the Protection Motivation Theory, than passive observation. These results highlight that behavioral engagement and control of action are as crucial as sensory immersion in shaping learning effectiveness and emotional resonance during safety training.

Navigation mechanics are designed according to the context of use: teleportation, or movement between fixed points, is generally preferred in wide or complex environments to prevent disorientation and motion sickness, while free locomotion is adopted in smaller or task - focused scenarios where user behavior needs to be monitored.

Non-Player Characters (NPCs), entities not controlled by users but by predefined scripts or autonomous behaviors, play a crucial narrative and functional role within immersive training environments. Their inclusion adds social realism and behavioral complexity, allowing users to interact within dynamic virtual ecosystems that mirror human interactions typical of the critical infrastructures. 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 [95]; in post - earthquake operations, they act as victims or rescuers, generating realistic and dynamic contexts for team training and crowd management [52, 42, 53]; in educational environments, they serve as instructors or peers who provide guidance and feedback [112]; and in industrial or confined - space scenarios, they function as virtual supervisors assisting with procedural operations [60]. 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. [95], 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. Such details significantly improve the sense of presence and emotional engagement, transforming VR environments from static

simulations into interactive narrative spaces. Within the storyline structure of serious games, NPCs serve both as narrative anchors, guiding the progression of events, and as instructional agents, delivering contextual information or corrective feedback during training. By integrating scripted social interactions, they foster cognitive immersion and empathy, encouraging users to interpret complex situations rather than simply executing pre-defined tasks. Ultimately, the inclusion of NPCs bridges the gap between procedural learning and human - centered experience, reinforcing the pedagogical realism of immersive simulations across all 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. [107] integrate dynamic difficulty adjustment and personalized feedback to sustain learner motivation and inclusion, in line with Universal Design for Learning (UDL) principles [133]. 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 [101; 32; M_067]. 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 [41; 73]. 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 [134], as discussed by De Lorenzis et al. [55], whereby temporary guidance structures are provided and gradually withdrawn as competence and autonomy increase. Similarly, the VR training platform by Gao et al. [35] incorporates adaptive guidance and assessment functions that adjust to the user's performance level. By analysing task completion, accuracy, and response time, the system dynamically adapts instruction and feedback, ensuring that both novice and experienced operators benefit from tailored learning experiences within the same immersive framework.

Feedback and Debriefing

Feedback mechanisms are structural to SG pedagogy. Evidence from [112] indicates that post - game reflection results in the most significant learning gains, and complementary findings from [107, 113] 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 [61]. Structured debriefing modules, including action logs, replays, and performance dashboards, support self - analysis and instructor facilitation [37; 38; 80]. 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 [135] and reflection - in - action during the exercise itself. Debriefing sessions, replay functions, and instructor - mediated discussions [37; 80; 38] 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 [95, 113] 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 [99; 36 38]. 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 (52, 58; 57). These configurations promote distributed situational awareness and collective intelligence, aligning with contemporary theories of social learning [129]. 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 in highly dynamic and uncertain environments, where multiple hazards - both natural and anthropogenic - can significantly disrupt their performance, safety, and service continuity. In rethinking how critical infrastructure is taught, hazards must be understood not as background variables but as the initiating forces that drive disruption and shape decision - making contexts. They define the conditions under which systems fail, adapt, or recover, and thus provide the foundation for effective preparedness and response training.

In the literature, hazards are broadly classified into Sudden - Onset Disasters (SUODs) [136] and Slow - Onset Disasters (SLODs) [137]. 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 [138], providing consistent terminology for triggers, footprints, and impact sequences, that support clear learning objectives. The Comprehensive School Safety Framework [139] 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 [140]. Compound and cascading risks such as storm - then - flood sequences require training to reflect real world escalation patterns [141]. Natural Hazard Triggering Technological Disasters (NaTech) events, where natural hazards trigger technological failures, and cascading interdependencies across systems [142] further complicate the operational landscape and must be explicitly incorporated into education and training frameworks.

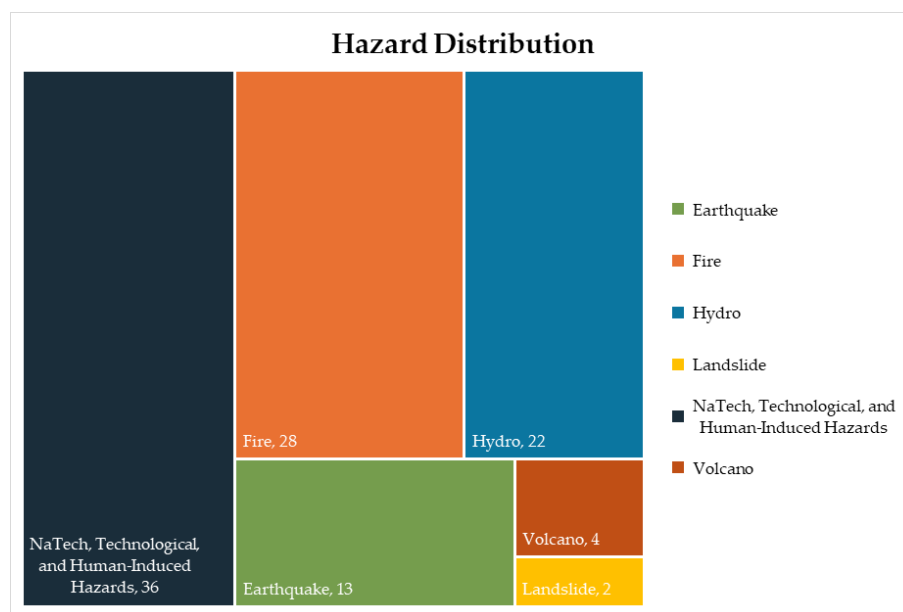


Figure 12: Distribution of hazard types across the selected papers. (Image created by the authors).

The distribution of hazards across the selected literature shows earthquakes as the most frequently addressed, followed by floods and fires, with other hazards treated in more specialized studies. To enable comparability across hazard types, each is analysed through a shared analytical framework that links the scientific logic of the phenomenon with its pedagogical and technological translation into simulation and immersive learning environments. For each hazard, four complementary dimensions are examined: (i) Objective - the educational and operational aims associated with understanding and managing the specific hazard; (ii) Applications - representative cases and training implementations drawn from the reviewed literature; (iii) Representation of the phenomenon - the models, simulations, and digital tools used to make the process visible and actionable; (iv) Limitations - current constraints, unresolved challenges, and transferability gaps between simulation and real - world performance.

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 [99; 36; 100; 43; 45; 74; 80; 40; 41; 25; 101; 123; 37; 72; 73; 38; 124; 39; 125; 56, 66]. A shared objective is to link rainfall, wind and water - level dynamics with concrete consequences for people, buildings and infrastructure, so that users can recognise 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 [40; 41; 37; 73]. Other tools target communities and planners and aim to support understanding of how defence portfolios and land - use choices shape inundation, damage and service disruption in specific catchments and cities [25; 36; 38; 124; 39; 125; 56, 66]. Technical simulations seek procedural competence for constructing and deploying mobile flood barriers under time pressure [101].

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 [99; 36, 96]. Tsunami tools link inundation maps and evacuation scenarios to help users understand run - up limits, arrival times and safe areas [100; 72]. Tropical cyclone and hurricane games focus on preparedness and response, training learners to interpret forecast products and plan resources ahead of landfall [74; 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 [40]. 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 [41; 37; 73]. Sea-level rise and coastal flooding experiences support climate-change teaching and adaptation debates in higher education and outreach programmes [99; 36]. 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 [43; 45; 80]. Tsunami simulations appear in school lessons and evacuation drills, where they underpin practice on route choice and timing [100; 72].

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 [41; 25; 36; 38; 124; 39; 125; 56, 66]. Immersive digital-twin frameworks show flood propagation over detailed terrain and help technical staff rehearse monitoring and warning procedures using synthetic or replayed events [25; 36; 38]. In operational contexts, the HCP-VR system [55] 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 practise assembly and deployment sequences under varying hydraulic conditions [101].

Hurricane logistics games support humanitarian and civil-protection personnel in rehearsing pre-positioning and routing decisions under uncertain forecasts [74].

Representation of the hazard phenomena

Inland flood representations range from conceptual models to data - driven simulations. In school -centred 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 [40]. Web - based games such as FloodGame use stylised 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 [41; 37; 73]. 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 [25; 36; 38; 56].

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 [99; 36]. Prototype systems for urban-scale tsunami evacuation similarly rely on 360° panoramas of real neighbourhoods, 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 [96]. Tsunami education tools use numerical inundation modelling 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 [100; 72]. 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 [124; 125; 56].

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 [43; 45]. 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 [74]. Here the focus is on path, intensity and forecast uncertainty rather than detailed damage mechanics.

Limitations

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 [99; 36; 100; 72]. 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 [41; 37; 73]. Work that frames flooding as risk assessment does foreground likelihood and consequences but still relies on deterministic model runs once inputs are fixed [40].

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 [25; 36; 38; 56]. Many serious games simplify hydrometeorological processes to reduce learning barriers and hardware demands, which suits awareness - raising but restricts operational use [41; 37; 73; 66].

The link to critical infrastructure performance remains partial. Several tools include roads, buildings and simple defences but lack explicit modelling of interdependent networks or cumulative damage from repeated events [41; 25; 36; 38; 124; 39; 125]. Training on mobile flood barriers concentrates on local deployment and does not propagate barrier performance into system - scale consequences [101]. Participatory simulations highlight trade - offs between measures and residual flood risk but seldom extend to detailed models of transport, energy or water systems [124; 125; 56, 66].

4.3.2. Landslide

Objectives

The landslide studies focus on rainfall - induced slope failures and their consequences [69; 70]. 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 [69; 70]. 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 [69; 70]. 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

Hazard is represented through responsive but simplified hillslope models. Each simulator presents one or more slopes described by a small set of variables, such as gradient, material strength, vegetation and hydrological state; mitigation and land - use choices modify these variables and thus the stability margin [69; 70]. The system responds with occurrence or absence of landslides and with indicators of damage severity. This preserves core causal relations between hydrological loading, strength and failure while keeping the decision problem manageable.

Feedback context is a deliberate design variable. In decontextualised modes, consequences appear as scores or abstract indicators, with little spatial information. In contextual modes, the same physical behaviour is embedded in simplified landscapes that show buildings, roads and people at risk; feedback includes visible damage to these elements after failures [69; 70]. Comparing these modes allows analysis of whether contextual, visually rich feedback produces more robust understanding than abstract feedback using the same hazard engine.

Limitations

To support controlled experiments, the landslide models compress real - world complexity. Slopes are schematic and homogeneous; interactions among multiple slopes, long runout distances and deep - seated failures are excluded [69; 70]. Triggering is based on simple rainfall or groundwater thresholds without explicit representation of temporal rainfall structure, antecedent moisture or complex geology. The tools therefore illustrate qualitative relations but are unsuitable for site - specific hazard assessment.

Stakeholder roles and institutional settings are narrow. Participants act as generic managers of protection budgets; there is no representation of infrastructure operators, emergency responders or households with distinct constraints. Zoning rules, warning systems and evacuation protocols are absent, which limits extrapolation to real governance contexts [69; 70].

Connections to critical infrastructure are implicit. Some scenarios reference buildings or roads as elements at risk, yet the simulators do not model network behaviour, redundancy or cascading failures. Infrastructure serves mainly as a damage indicator, not as a system with its own dynamics. For a review centred on critical infrastructure, these landslide tools mainly inform how individuals learn about slope risk and feedback, while infrastructure - focused landslide risk and asset management re-main under - represented.

4.3.3. Earthquake

Objective

Among the natural hazards affecting critical infrastructure, earthquakes are among the most extensively studied and simulated phenomena in education and professional training. Because of their capacity to trigger cascading effects, from structural collapse and fire outbreaks to service interruptions and socio-economic disruption, preparedness is essential for ensuring both system continuity and public safety.

With regard to the temporal dimension of seismic events, typically divided into foreshock, main shock, and aftershock stages, training applications primarily focus on the latter two 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 [53]. School - based programmes have repeatedly demonstrated that structured feedback and post - simulation reflection significantly improve understanding and knowledge retention among both students [18, 107, 112] and teachers [97] 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 [19, 42, 52, 111].

Together, these complementary objectives integrate cognitive, procedural, and emotional preparedness, forming the pedagogical foundation for multi - level learning environments that combine analytical rigour with experiential realism.

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 [19, 67] and immersive VR-SGs [42, 52, 53, 111, 112, 113] 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 [18, 97, 107, 112]. 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 [53, 112]. 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 programmes 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 [95, 111], while the multi-hazard system developed in [53] 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 operationalise institutional guidelines within participatory and educational settings, fostering consistent safety behaviours 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 se-lection and coordination under uncertainty [42]. In more advanced configurations, operators are immersed in virtual reconstructions of collapsed urban areas, performing triage and hazard recognition tasks [52]. 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 particularly significant example is represented by the VRRescue project, developed and tested within the Urban Search and Rescue Training Center of the Italian National Firefighters Corps located in Pisa [52]. The facility integrates a large-scale physical mock-up of collapsed structures with a virtual counterpart derived from photogrammetric 3D models of real post-earthquake environments. Professional rescuers use the simulation to practice victim localization, triage, and coordinated intervention, confronting realistic damage conditions that mirror those encountered during

operational missions. By combining virtual and physical modules, the Pisa initiative demonstrates how immersive technologies expand national training capacity, 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 [67].

At a more systemic and multi-hazard level, dynamic modelling frameworks capture the earthquake as a complex process capable of triggering secondary hazards such as fires, explosions, or landslides, and propagating effects across interdependent infra-structure networks [19]. 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 [54, 107, 113], schools [97, 112], and hospitals [95, 111], to urban neighborhoods and open public areas [19, 42, 52, 53, 67].

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 [18, 107, 112]. 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 [111].

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 [95]. 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 [95].

Beyond perceptual realism, simulation research increasingly focuses on the computational modeling of structural damage. In the Auckland City Hospital simulation [95], 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, achieving a realistic depiction of seismic effects without compromising performance. This approach reflects a broader methodological trend across VR earthquake simulations: dynamic behaviors are scripted procedurally, while static damage states are precomputed or visually 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-storey buildings. Analytical frameworks compute damage externally through quantitative models and import results as pre-processed data [19], whereas educational simulations often rely on simplified procedural logic sufficient for pedagogical realism [107, 111, 112].

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 [19]. Qualitative representations, typical of educational simulations [107, 111, 112], 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 modelling [53]. 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.

These varied approaches to perceptual and computational realism reveal both the technological maturity and the current constraints of earthquake-simulation research.

Limitations

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

- Physical fidelity vs. interactivity. Realistic ground motion and structural de-formation 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 [58; 57].
- Validation and curricular integration. Few studies measure long-term retention or validate VR performance against real emergency behaviour. Embedding immersive training into national curricula remains an ongoing challenge [97, 107, 112].

Despite these constraints, immersive earthquake simulations mark a decisive step in resilience education, bridging analytical rigor, experiential learning, and behavioral adaptation. By combining engineering precision with emotional realism, they strengthen preparedness across both public and professional domains.

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 [78; 79]. Immersive VR field trips reproduce access to remote or dangerous volcanic sites so that university students and researchers can practise mapping and measurement tasks in realistic outcrops without field travel [98]. A probabilistic event - tree model, BET_UNREST, targets scientific teams, seeking to familiarise them with structured probabilistic diagnosis of unrest and short - term eruption likelihood during crisis simulations [71].

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 [78]. The ARGEO mobile app delivers similar content on smartphones, with labelled 3D volcanoes, brief videos and embedded quizzes used as pre/post tests of understanding [79]. 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 [98]. 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 [71].

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 [78]. 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 [79]. 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 [98]. 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 [71].

Limitations

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 [78; 79]. The VR fieldwork system prioritises geometric realism but omits dynamic eruptive phenomena and provides limited systematic evidence on learning outcomes across student cohorts [98]. 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 [71]. Across these studies, infrastructural assets appear, if at all, as part of the surrounding landscape, and there is no explicit modelling of infrastructure performance or cascading effects under eruptions, which restricts direct application to critical - infrastructure - centred training.

4.3.5. Fire

Objective

Within the domain of critical infrastructure, fire constitutes a cross-cutting and recurrent hazard: a rapid combustion process that, through the release of heat, smoke, and toxic gases, can compromise the tenability of spaces and the operability of systems within minutes. In the context of training and education, fire must be addressed not only as an isolated emergency but as a systemic phenomenon affecting multiple interdependent infrastructures - energy, telecommunications, transport, and water, and therefore as a critical component of resilience education.

From a risk perspective, the literature consistently frames fire around three main vulnerability domains: (i) Operational continuity [22, 30, 46, 57, 77, 82, 93, 110, 126]; (ii) Occupant behavior and evacuation [20, 21, 23, 28, 47, 48, 57, 58, 65, 76, 82, 84, 85, 87, 91, 94, 102, 108, 115, 119, 121, 143]; (iii) Energy escalation [22, 24, 103, 116, 120].

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

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

Within the analyzed corpus, approximately thirty directly or predominantly address fire, focusing on training and simulation applications. Following a hazard-exposure-vulnerability-consequence perspective, events can be categorized by origin and operational domain, illustrating how ignition mechanisms, exposure conditions, and infrastructural settings jointly determine risk profiles and training priorities.

Natural or wide - area fires occur under adverse climatic and meteorological conditions or within all - hazards 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 [46, 47, 85].

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 [91].

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 [24, 93, 103].

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 [110, 120, 126], railway [82, 119], underground/tunnel [28, 57, 58, 108], and hydrocarbon supply chains [30, 77], 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 [84, 94, 115, 121], universities [23, 48, 87, 102], airports conceived as building systems, offices/civil and commercial buildings [20, 21], and training towers [65].

Collectively, the literature demonstrates that virtual fire-safety training applications cover a broad continuum, extending from individual awareness programs to complex operational simulations reproducing realistic multi-agent emergencies. On the non-immersive end are simulations and online (desktop-based) platforms

designed to illustrate evacuation plans and behavioral guidelines - focusing on route identification, exit recognition, awareness of hazard sources, and the proper handling of hazardous items/materials - primarily targeting occupants and visitors. Typically, low-cost and highly scalable solutions include web/virtual-world environments with assessments of knowledge, retention, and attention [48], desktop serious games for schools [84], and “hybrid” collaborative environments with a non-immersive option [47].

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 [57, 58, 76, 85, 94, 102, 103, 110, 115, 119, 120, 126]. 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 [21, 23, 24, 28, 30, 65, 82]. By contrast, studies on synchronous multi-role exercises and joint decision-making in complex scenarios via multi-user collaborative platforms remain limited [57, 58, 47, 126].

Representation of the phenomenon

The virtual representation of fire and smoke propagation follows a methodologically consolidated pipeline. Most mature studies 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 8: a, Fire model; b, Smoke model.

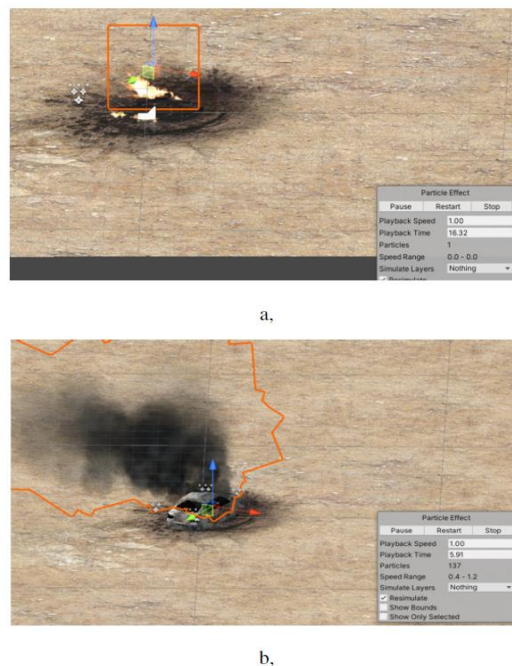


Figure 13: Representation of fire and smoke phenomena, adapted from Thach et al. [110]. © 2024 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

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 optimised for real-time performance [58]. 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 [94]. 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 [30, 110]. At the opposite end, desktop and web-based solutions remain more scalable but less behaviourally 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 path-finding logic [21];
- metaheuristics such as Particle Swarm Optimization (PSO) shorten evacuation time and path length [24];
- Deep Reinforcement Learning (DRL), combined with IoT sensors and Digital Twin (DT) data, enables adaptive guidance, re - routing occupants dynamically during evolving emergencies [23].

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 [21, 23, 24, 28, 30, 65, 82]. This integration supports data - rich, adaptive scenarios, extending the role of fire simulation from training to operational decision support.

Limitations

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 [58, 94].
- 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 [94].
- Collaborative synchronization. In multi-user contexts, latency, avatar embodiment, and limited spatial audio undermine teamwork and coordinated decision-making [57, 58].
- Validation and institutional integration. Few studies assess long-term retention or embed VR fire training in professional curricula, limiting adoption in formal education [115].

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 [58, 94,115].

Overall, fire simulations exemplify the integration of computational modelling, human-factor design, and immersive learning. By translating complex thermofluid phenomena into experiential scenarios, they advance both individual preparedness and systemic resilience across critical infrastructure domains.

4.3.6. NaTech, Technological, and Human-Induced Hazards

Objective

Natural Hazard Triggering Technological Disasters (NaTech), technological hazards, and human-induced hazards define a continuum between natural and anthropo-genic risk conditions in critical infrastructures. In practice, adverse events rarely originate from a single cause: they emerge from the interaction between natural triggers, intrinsic technological vulnerabilities, and human and organizational factors across tightly coupled systems. Within this continuum, NaTech events occur when earth-quakes, floods, storms or other environmental extremes initiate failures in engineered structures and processes; technological hazards arise from process instability, equipment ageing, or failures of supervision even in the absence of external shocks; human-induced hazards include both unintentional errors and violations, and intentional acts such as sabotage or terrorism that exploit existing vulnerabilities.

In this context, immersive simulation and extended reality (XR) systems are used to convert high-risk, low-frequency situations – often impossible or unacceptable to re-produce on site – into controlled learning experiences. Across open-pit mining, construction, process industries, transport systems and power infrastructures, virtual environments reconstruct work sequences, near-misses, equipment malfunctions and critical environmental conditions, exposing trainees to the consequences of their actions without exposing them to physical danger.

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.

Consequently, training aims to embed human-machine interaction and digital supervision within operational readiness: operators learn not only how to execute tasks, but how to interpret alarms, cooperate with automated systems and anticipate failure propagation across interdependent networks. In this sense, NaTech, technological and human-induced scenarios become a crucial component of resilience education, linking the engineering of protection and control systems with the behavioral and organizational competencies required to operate them safely in complex, evolving environments.

Applications

In high-technology systems, risk does not appear as an anomaly, but as an intrinsic possibility that emerges from the interaction among complex components, stringent procedures, and human limitations. In this context, XR applications for operational safety are primarily oriented toward training on complex operational and maintenance sequences and on the coordinated management of inspection, maneuver, and emergency response phases. Training systems for electrical safety [31, 89, 117] propose scenarios in which operators practise 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 [117]. In distribution networks and power generation, immersive platforms for substations and hydroelectric power plants [26, 64, 89] 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 [26, 30]. In the energy sector and process industry, immersive scenarios for the maintenance of marine engines and generator sets [104, 114, 122] and for safety training in oil and gas facilities [92] 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 [104].

In the construction and underground works sector, VR and VAR environments are used to anticipate high-risk site conditions, where the co-presence of machinery, spatial constraints, and rapidly evolving operational phases generates configurations that are difficult to control in situ. Safety training systems for open-pit quarries [59] and infra-structure excavations [33] 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 [83, 88]. 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 [49, 51, 68]. The theme of working at height and in emerging energy contexts is addressed through simulations of wind tower erection [50] and maintenance of photovoltaic systems [29], in which participants practice access procedures, use of 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 [60], 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 [32].

Another group of applications focuses on emergency management and techno-logical 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 [34, 86]. 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 [35]. 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 [30, 77]. 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 [64, 105]. 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 [22, 24, 103]. In the aero-nautical 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 [27, 90].

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 [75, 118]. 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 [32]. 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 [59, 106, 109, 117]. 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 [61].

Collectively, these applications converge toward a unified pedagogical space in which technological precision and behavioral realism are jointly cultivated. By combining procedural rigor, cognitive engagement, and emotional calibration, immersive simulations across the NaTech–technological–human-induced continuum transform complex emergencies into actionable training experiences that strengthen both system safety and human preparedness.

Representation of the Phenomenon

In the contributions included in this cluster, NaTech, technological and human-induced risks are represented through virtual environments that articulate the phenomenon along three intertwined levels: the spatial and infrastructural configuration, the evolution of technical–industrial processes, and the actions of human subjects 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 [30, 33, 34, 59, 89, 105]. 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 [75, 96]. 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 [33, 59] and for infrastructural and energy construction sites [29, 68]: 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 [29, 33, 59, 68]. 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 shut-downs [29, 59, 77]. 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 [33, 68, 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 [59, 86, 92, 114]. Users interact with the environment via controllers, pointers or gesture-based interfaces to inspect, select tools, confirm procedural steps and operate controls [27, 29, 33]. 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 [22, 31, 64, 117].

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 [30, 34, 77]. 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.

Limitations

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

- **Model coupling:** consistently integrating environmental triggers with industrial process models remains technically complex and data-intensive; in most studies, the natural hazard is treated as a simplified narrative background and attention is focused on downstream consequences, without fully representing the physical and organizational propagation chain of the event.
- **Emotional balance:** representing traumatic or violent events requires careful calibration in order to preserve psychological safety without reducing pedagogical depth; only a few contributions explicitly discuss criteria, guidelines, or metrics for tuning the intensity of audio-visual stimuli, the level of induced stress, and the differentiation of emotional load according to different user profiles.
- **Behavioral validation:** few studies verify the transfer of simulated reactions into real-world behavior or their retention over the long term; evaluation focuses predominantly on knowledge tests and immediate self-report measures, while robust longitudinal evidence is still lacking to link immersive training to observable changes in operational practices, near-miss indices, and accident rates.
- **Systemic integration:** multi-user coordination and the modelling of interdependencies across infrastructures remain limited, reducing the realism of cross-sector crisis simulations; the unit of analysis is often the single plant or department, and only rarely are impact chains that span multiple networks (energy, transport, communications, emergency services) explicitly simulated.

Considered together, these limitations delineate a state of the art in which immersive simulations describe hazardous conditions and individual behaviors effectively, but still struggle to fully represent the physical, temporal, and systemic complexity of the hazards that characterize contemporary critical infrastructures.

4.4. Critical Infrastructure domains

In the context of CI resilience, immersive and data - driven technologies are being increasingly deployed across diverse sectors, from energy and transport networks to healthcare systems and civil protection agencies. Each domain presents distinctive operational logics, spatial configurations, and vulnerabilities, yet the pedagogical objective remains constant: to develop systemic awareness and procedural competence in environments where safety, service continuity, and coordination must coexist.

Within these domains, simulation does not merely replicate physical spaces; it operationalises interdependence, between assets, processes, and human roles, turning infrastructures themselves into learning ecosystems.

Training applications frequently mirror the operational structure of CI systems, where interdependencies between assets, services, and actors determine overall performance during crises. In this perspective, simulation environments reproduce not only material configuration of infrastructures but also their socio - technical hierarchies, supporting coordinated learning across multiple organizational layers.

At the same time, several studies treat the urban built environment as a form of socio - technical infrastructure in its own right, the spatial framework that sustains community resilience and everyday functioning. Figure 15 summarizes the distribution of the reviewed studies across critical infrastructure domains, highlighting how training and simulation applications concentrate in a limited set of sectors while progressively expanding toward a wider range of socio-technical systems.

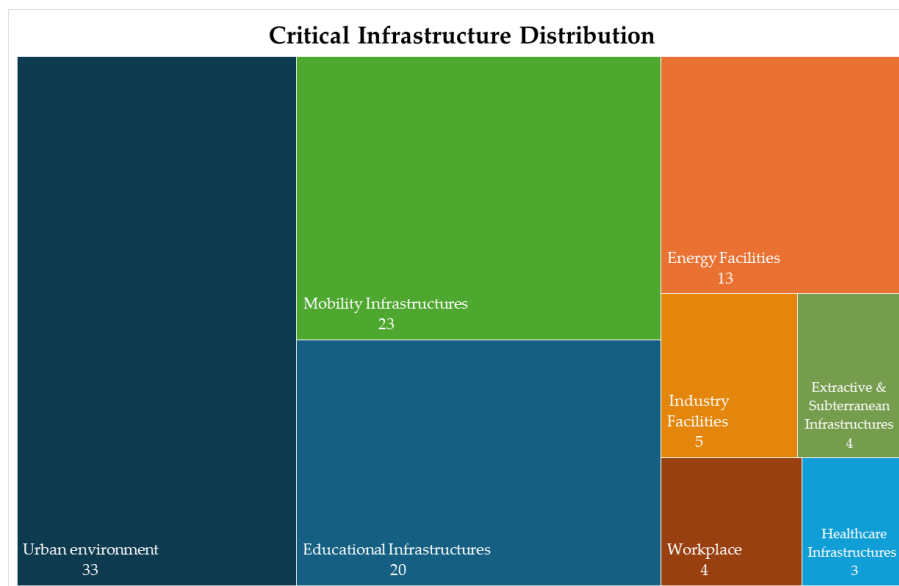


Figure 14: Critical Infrastructure distribution over selected papers. Image created by the authors.

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 both economic functionality and emergency accessibility. Their operational complexity stems from the intersection of confined geometries, high user density, and continuous interdependence with energy, communication, and safety networks. The geometric continuity of infrastructural elements (tracks, carriageways, tunnels) and the presence of nodes and specialised technical spaces (driver cabins, engine rooms, loading areas, construction sites) directly determine the level of exposure to risk. Within such 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. Rather than merely providing spatial description or visualisation, these systems operate as instruments for orchestrating interactions among heterogeneous actors (passengers, pedestrians, operators, emergency response teams, maintenance technicians) throughout the entire life cycle of the infrastructure, from design and construction phases 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 modelled as digital twins to train coordinated crisis response in confined, high-density environments. The EGCERSIS project [108] 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 [86], as well as in internal corridor segments characterized by constrained geometries, specialized equipment and strong dependence on signaling logics and centralized control [119]. At a broader scale, the digital-twin model for derailment scenarios presented by Xu et al. [34] 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 modelled together, enabling the planning and testing of recovery operations within a high - fidelity reconstruction of real line segments. Expanding this modelling approach to the train itself, the locomotive crew VR training system [35] 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 [61] 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.

In underground and tunnel infrastructures, the integration of BIM and VR allows for high - fidelity reconstructions of linear corridors, escape routes, and technical chambers. The BIM-VR model for emergency management in motorway tunnels [28] demonstrates how the layout of escape routes, SOS niches and installations, enriched by semantic metadata, is essential for constructing plausible and reusable scenarios, even though such assessments remain qualitative and limited to a single case study. Extending this approach, the FrèjusVR system [57, 58] exemplifies multi-user and multi-role learning: firefighters, truck drivers, and civilians act concurrently within the same digital replica of a road tunnel, practising alarm activation, communication, and decision - making. The resulting scenarios not only test procedural timing but also social coordination, showing that mutual visibility among avatars significantly enhances collective situational awareness and perceived realism.

At the urban scale, this perspective extends to metro systems, where the VirtualSafeConDM framework [68] 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 [77] highlight the specificity of roadside hazards and the need to train highly specialised

operators. VR applications for hazard recognition in motorway work zones [51, 88] reconstruct corridors and construction areas - as shown in Figure X - to systematise hazard identification and decision - making. The Immersive Cross - platform X3D system [49] 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 [96] 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 use of private vehicles during evacuations and the congestion it generates [72], or the management of hazardous - goods transport at the interface between industrial logistics and the public road network [77]. Across these cases, roads and tunnels are treated as infrastructures whose geometry, capacity and connectivity directly condition the feasibility of protective actions.

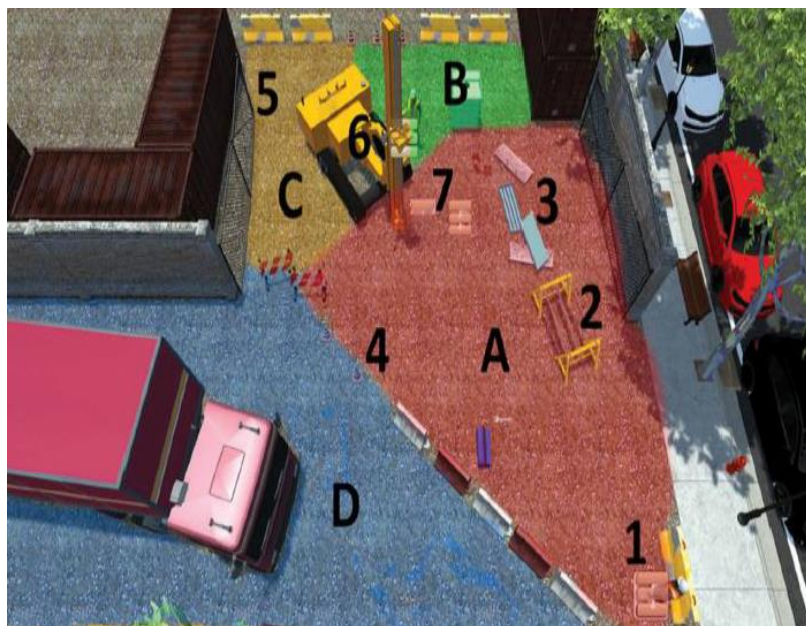


Figure 15: Work zone of the VR scenario. Reproduced from [88], © 2023 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0)

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 [90] and AR-based pre-flight inspection [27] show that simulated scenarios and digital overlays support procedural standardisation and situational awareness, strengthening adherence to safety protocols among flight crews and maintenance personnel.

Beyond land-based and airport systems, maritime transport infrastructures - which include ports, shipping routes and onboard technical spaces such as engine rooms - constitute an additional layer of the mobility network, in which navigation, propulsion and emergency management are tightly coupled within highly confined industrial interiors. In this domain, ship engine rooms emerge as critical industrial subsystems of the transport infrastructure, where propulsion units, auxiliary systems, piping networks and control panels are concentrated in compact, evacuation - critical and operationally dense spaces. In the training system described by Hamed-Ahmed et al. [126], the engine room and, in parallel, the galley are identified as areas with the highest incidence of fires: drill scenarios are structured according to different levels of severity and controllability, requiring trainees to locate the fire source, activate the procedures prescribed by SOLAS

(the International Convention for the Safety of Life at Sea - alarm, communication with the bridge) and decide between local extinction and evacuation along predefined escape routes. A further noteworthy example is the ShipSEVR project [122], in which the engine room of a platform supply vessel is modelled as a high-fidelity technical space, where generator sets and auxiliary systems are integrated with plant schematics and digital documentation accessible in VR, shifting the focus towards maintenance procedures and safety practices.

Complementarily, Thach et al. [110] develop a maritime VR training setup coupled with a shipboard fire-alarm hardware architecture, modelling container-ship spaces (e.g., engine room, electric room and bridge) in Unity and linking alarm panels/HMI monitoring to the virtual scenario to let trainees detect and localize fire events and re-hearse onboard response procedures. Other studies on electrical-safety training in the maritime domain [120] further extend this perspective to the high-voltage onboard electrical system, confirming that the ship's technical interiors - both mechanical and electrical - constitute essential nodes for the overall resilience of the maritime transport system. More generally, the experimental study by Makransky and Klingenberg [114] shows that, in maritime safety training (for example, dynamic risk assessment during mooring operations), VR simulators can outperform traditional instructor - led training in terms of motivation, perceived learning and intentions for behavioral change, high-lighting the potential of immersive solutions as a scalable tool for standardised and just - in - time training across global fleets. These contributions show that maritime transport requires immersive environments capable of simultaneously representing navigation constraints, technical interiors and emergency response strategies.

Taken together, mobility infrastructures provide a paradigmatic field for understanding how immersive learning can align human cognition with complex, networked systems. Across all transport modes, the evidence shows that virtual and mixed - reality environments transform linear, high - density infrastructures into shared cognitive spaces where procedural accuracy, communication, and adaptive reasoning can be rehearsed safely and iteratively.

4.4.2. Extractive and subterranean infrastructures

Extractive and subterranean infrastructures - encompassing underground mines and open - cast quarries - represent inherently critical environments, where the inter-action between unstable materials, mechanical operations, and constrained spaces produces a persistent state of risk. Activities near ignition sources, the handling of weak or fragmented rock masses, and the possible presence of toxic gases make fires, collapses, and reduced visibility recurrent hazards. What distinguishes these two contexts is their operational setting: underground mining unfolds within confined voids, ventilation networks, and limited egress routes, while open - cast extraction occurs in ex-posed environments characterised by excavation fronts, variable slopes, and the need for continuous control of stability and material handling.

Across the reviewed literature, two key principles emerge for workforce training in these domains: spatial continuity and operational coherence of the learning environment [93, 59].

The simulation developed for the marble quarries of the Apuan Alps [59] exemplifies these principles. It reconstructs a real site as a system of interconnected scenes linked by access ramps, where yards, quarry faces, and drilling areas are represented with realistic elevation data and populated with virtual machinery and operators. This configuration reproduces typical conditions of instability, manoeuvres in confined spaces, and human - machine interference, creating an immersive environment in which participants can rehearse coordination and safety protocols in context.

For underground mines, training for Australian rescue brigades adopts a whole - of - mine model that virtualises approximately 50 km of galleries and roadways, integrating fire and smoke - release scenarios along a continuous network of drifts [93]. This large - scale simulation reproduces not only geometry but also the sensory and operational complexity of emergency response underground - darkness, visibility gradients, heat, and noise - allowing teams to practise navigation, communication, and time - critical decision - making under realistic constraints.

This approach is further extended by Kaarlela et al. [105], who construct a high - fidelity virtual environment from a laser - scanned point cloud of mine cavities at depths of around 400 m. The resulting model, integrated into a Unity - based simulation framework, supports interactive training on emergency response to fires, explosions, haul - truck accidents, and co - worker injury. Workers engage directly with realistic

representations of equipment and spatial configurations, allowing the simultaneous training of procedural execution, spatial reasoning, and team coordination.

Taken together, these studies frame the mine as a continuous infrastructure of workspaces and access routes, where connectivity, atmospheric conditions and the presence of heavy equipment directly define manoeuvring margins, evacuation paths and intervention strategies.

Across these applications, quarries, mines, and related infrastructures such as trenches and drilling pads are treated as socio - technical systems, where excavation volumes, functional areas, and safety perimeters are modelled and manipulated in ex-tended reality to reproduce realistic gallery networks and open - pit morphologies. This approach supports navigation, hazard recognition, rescue training, and operational planning in both underground and open - air industrial contexts. The combination of accurate topography and contextual auditory feedback - wind, machinery, drilling, and cutting noises - strengthens situational awareness and procedural learning, demonstrating how XR can reproduce the perceptual and operational complexity of real ex-traction sites. In several studies, high - fidelity geometric reconstructions of tunnel and cavity networks [105] are coupled with process - simulation logics and robotic systems, transforming the mine into a testbed for digital - twin concepts and advanced automation. These hybrid environments anticipate, in embryonic form, many of the solutions that later appear in industrial and energy domains, where immersive technologies evolve from spatial training tools into integrated platforms for simulating complex plants, hazardous processes, and control infrastructures.



Figure 7. VR course on primary cutting upstream (SO1). Before starting horizontal cutting, the user interacts with the pointer, verifies the compliance of the operational phase checking the safety distances from the machine (a), positioning the diamond wire guards in order to avoid whiplash in the event of wire breakage during horizontal cutting (b). Source: authors' processing by Software Simulation version 1.2.1.

Figure 16: VR training for primary upstream cutting (SO1): safety-distance verification (a) and positioning of diamond wire guards before horizontal cutting (b). Reproduced from [59], © 2025 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0)

4.4.3. Energy facilities

Energy infrastructures represent a core subset of CI, where the continuous generation, conversion and transmission of power are closely linked to high technological hazards such as fire, explosion, release of hazardous substances and blackout. Within the corpus, this domain encompasses electrical power systems and substations, gas-fired power plants, onshore and offshore oil and gas (O&G) facilities, and renewable energy plants such as hydropower stations, wind towers and photo-voltaic farms. These systems range from relatively compact configurations, for instance gas power plants centred on a few generator sets within a single building, to highly distributed production chains that span extraction, processing, storage and transport across large territories. Despite their heterogeneity, these systems share a fundamental educational challenge: training operators to manage complex, high-risk environments where spatial configuration, process control, and emergency procedures are tightly interwoven. Immersive and data-driven applications operate here as safe surrogates for high-risk environments, enabling user to explore plant layouts, identify safe and unsafe paths, and rehearse emergency, maintenance and inspection procedures that would be too dangerous or costly to replicate on site.

The reviewed literature covers four main infrastructural configurations: electrical systems, gas power plants, Oil&Gas facilities and renewable energy installations, showing how VR, AR and XR - based simulators

couple spatial models, process logics and safety mechanisms to enhance preparedness, operational continuity, and systemic resilience.

Within the electrical power sector, immersive applications focus on substations, technical rooms, and work sites along live lines, where operations involve high-voltage components and sequential safety procedures. Substation simulators [89] reconstruct actual high/medium-voltage facilities in 3D, including bays, switching equipment and operator pathways, allowing trainees to rehearse opening and closing of circuit breakers, disconnectors and earthing switches while visualizing the consequences of incorrect sequences. Low-voltage training systems [117] further re-produce full operational workflows—from PPE selection and lock-out/tag-out procedures to voltage verification, helping learners internalize each step under realistic conditions. Studies comparing different feedback modes (visual, textual, auditory) show how multimodal cues can improve comprehension, reduce cognitive load, and sustain motivation [31]. VR - based education systems aim to strengthen engagement and adherence to safety practices by simulating electric shock and fall accidents during elevated component replacement, explicitly highlighting hazard points along the entire operational process [109]. Other platforms extend training to risk prevention and robotic assistance, for example using VR to test teleoperated interventions near energized equipment, showing how immersive environments can also support the design and validation of safety robotics [22].

In gas power plants (GPPs), the interaction of combustion, pressurized equipment, and confined environments introduces additional risks that require high procedural accuracy. Immersive simulations for GPPs [103, 104] reproduce complete sequences of maintenance and emergency management: participants identify leaks, execute shut-down procedures, and locate main gas valves under rapidly changing conditions, or perform routine maintenance operations – such as air filter replacement – in accordance with the plant's HSE requirements [104]. The simulation proposed by Kwegyir-Afful [103] exemplifies this logic, modelling a conceptual gas-engine facility where a leak triggers a fire and trainees must safely evacuate through the nearest exit and isolate the fuel supply. These scenarios demonstrate how immersive technologies allow repetitive, feedback-driven practice of critical actions while maintaining physical safety. By visualizing the relationship among process units, escape routes, and control devices, these systems reinforce spatial reasoning and adaptive behavior.

In the transition from natural GPPs to Oil & Gas (O&G) infrastructures, the focus shifts from relatively compact energy systems - centred on a few generation units housed within a single building - to much more distributed production chains that encompass hydrocarbon extraction, processing, storage and transport. Whereas in GPPs the risk profile is governed mainly by the fuel - combustion chamber - exhaust circuit and by the management of a confined high - energy volume, O&G infrastructures in-volve large inventories of flammable substances, extensive piping and tank networks, complex process units and a strong integration with logistical and transport systems. It is therefore not surprising that the study by Mujtaba Asad et al. [92] on Pakistani Oil & Gas industries shows that this sector remains among the industrial domains with the highest incidence of major accidents, while at the same time highlighting a still largely unmet need for VR - based solutions specifically dedicated to safety training. In the corpus devoted to the O&G sector, onshore configurations - land - based facilities such as depots, terminals and process units connected to transport networks - and offshore configurations - platforms and marine units for on - board extraction, processing and power generation - are treated jointly because they belong to the same infrastructural chain and share a common core of hazards and plant logics. Although they differ in operational context, accessibility and evacuation strategies, the infrastructural approach to the facility - based on processes of separation, compression, pumping and storage of flammable fluids, potentially explosive atmospheres, work at height and confined spaces - remains substantially analogous.

In these infrastructures, the risk profile is dominated by the presence of large volumes of flammable or explosive hydrocarbons, pressurised equipment, ATEX atmospheres, highly constrained access and egress routes, and a systemic dependence on standardised operating procedures and a consolidated HSE culture. Mujtaba Asad et al. [92] shows that, within this framework, VR - based vestibule training has the potential to reduce injuries and fatalities, but must contend with economic and infrastructural barriers, as well as organisational resistance to the adoption of new technologies.

In onshore contexts, the oil depot system [30] reconstructs the site as a high - risk node - comprising tank farm, loading areas, piping networks and fire - fighting equipment - and employs separate inspection and

emergency modules to let users explore infrastructural anomalies and fire/explosion scenarios along predefined routes and operational roles.

Offshore, by contrast, study [26] models the platform power system as an isolated micro - energy infrastructure, virtualising the onboard substation and electrical equipment at real scale within a structured training environment, where switching sequences, fault conditions and operating states are controlled via programmable logic controller (PLCs). In both cases, VR makes the relationship between plant layout, risk - control devices and intervention procedures explicit; however, the depot application emphasises the spatial and collaborative dimensions of emergency response, whereas the platform scenario privileges the depth of modelling of power systems and plant behaviour.

Complementing these plant - and system - level perspectives, some contributions focus on the upstream and logistics segments of oil and gas infrastructures through analytical and extended - reality approaches. Machine - learning pipelines calibrated on core - flooding experiments are used to derive parameter distributions for enhanced - recovery models, supporting scenario analysis for reservoir development and production planning within the broader energy infrastructure [44]. Mixed - reality scenarios for accidents involving road tankers carrying dangerous goods, in turn, train crisis managers and emergency responders at the point where industrial supply chains intersect with public transport corridors [77]. Together, these works emphasise that oil and gas infrastructures extend from the reservoir to the roadway, and that both high - fidelity simulation and interactive training have a role in supporting their safe operation.

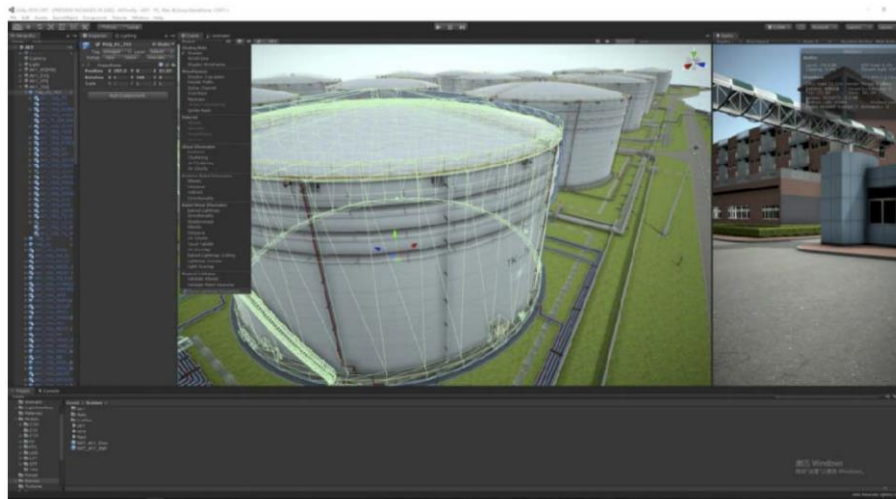


Figure 1. System development interface

Figure 17: System development interface of Oil and Gas plant. Reproduced from [30], © 2019 The Author(s), distributed under the Creative Commons Attribution License (CC BY 3.0)

Within renewable-energy subdomains, energy infrastructures are conceived as distributed systems strongly dependent on environmental conditions and characterized by hybrid risk profiles: electrical and mechanical hazards typical of generation facilities coexist with work-at-height exposure, difficult access, and variable weather. Hydro-power-plant simulations, such as Righi et al. [64], reconstruct a 132 MW reference facility with machine halls, control rooms, and access routes linked to hundreds of operational commands, enabling the training of multiple resilience skills—from decision-making and coordination to management of operational constraints under grid disturbances. From an infrastructural perspective, the plant is treated as a continuous socio-technical system in which the interaction between physical layout, supervisory systems and power-grid constraints are simulated in an integrated way to assess operators' ability to maintain performance under abnormal conditions.

Wind-tower simulators (Li et al. [50]) model vertical infrastructures with high fall and structural-collapse risk, guiding users through the sequential assembly process and emphasizing hazard recognition during each phase. Conversely, photovoltaic systems [29] interpret installations as diffuse infrastructures where electrical, fire, and height risks converge. In this case, based on field analyses, VR/AR gamified scenarios are designed for workers engaged in the installation, maintenance, and cleaning of photovoltaic (PV) systems. The virtual environment reproduces façades equipped with photovoltaic panels, manlifts, lifelines, and anchor points, structuring the workflow into four stages: PPE selection, preparation, work at height,

and closure, with predefined performance thresholds and simulated incident outcomes triggered by repeated errors.

Taken together, these examples illustrate how immersive and data-driven technologies serve as experiential laboratories for energy-sector training. By virtualizing substations, engine halls, tank farms, offshore platforms, machine halls, wind towers, and PV fields, XR simulators render the relationship between plant configuration, process logic, and protection systems both navigable and measurable. They enable operators and trainees to observe, interpret, and act within realistic yet controlled environments, improving procedural accuracy and cognitive readiness. At a systemic level, these environments pave the way for tighter coupling between training platforms, digital twins, and real-time operational data, linking safety education, predictive maintenance, and resilience management into a unified framework.

4.4.4. Industry Facilities

Industrial infrastructures constitute a core component of Critical Infrastructures, in which production lines, process units, research laboratories and control systems are organised in configurations characterised by high plant density and strong functional interdependence. In these environments, the risk profile is dominated by the presence of hazardous substances, pressurised equipment, moving machinery and operations in confined spaces, as well as by a high degree of automation and dependence on standardised operating procedures. In the analysed corpus, this domain includes both manufacturing and process facilities (e.g. assembly lines, production departments, construction sites and proto-plant configurations) and chemical and research laboratories, which operate as modular micro-plants with high variability in equipment and sub-stances. In both cases, immersive applications are used to make explicit the spatial structure of work environments, the sequence of operations and critical interaction points between people, equipment and safety systems, thereby enabling operators to be trained in hazard recognition, procedure implementation and incident management within highly complex techno-organisational contexts. This factory-centred perspective is reflected in the VR occupational health and safety training system by Lacko [106], which targets employees of industrial companies and reproduces both production and non-production areas through scenarios drawn from the normal operating practice of the factory, including stair circulation, warehouse logistics with racks and forklift traffic, and safe interaction with industrial machinery and equipment.

On the side of production facilities, the IVR platform for confined-space safety developed by Evangelista et al. [60] treats tanks, vessels, silos, manholes and under-ground chambers as critical sub - infrastructures within the plant. The virtual environment reconstructs enclosed volumes with limited access points, pipe connections and level differences, embedding step - by - step operational procedures for entry and work in confined spaces. From this perspective, the confined space is not only a training scenario but a node of the plant network, in which geometric configuration, atmospheric conditions and the presence of equipment jointly define error margins, safe routes and mitigation strategies.

In the case of chemical laboratories, both studies treat the laboratory as a micro process infrastructure, but with different emphases. In the training system for laboratory inspection [75], the environment is decomposed into 15 scenes connected by door tags, ranging from the entrance to the personal protective equipment (PPE) dressing area, from the workbench to the fume hood and the storage area: the laboratory is thus modelled as a sequence of functional spaces traversed by the inspector, in which safety and security hazards are “planted” along the path and made explicit through interactive hotspots. In the VR serious game for laboratory safety [118], by contrast, the company’s chemical laboratory is represented as a single operational environment in which benches, equipment and protection devices form the backdrop for tasks of risk identification, risk minimisation and safe execution of experiments. From a comparative standpoint, [75] emphasises the laboratory as an inspection infrastructure, articulated into nodes and links to be traversed systematically, whereas [118] conceives it as an immersive work infrastructure, in which layout and equipment primarily serve to contextualise player actions and to link operational choices, errors and consequences within a single experimental space.

Beyond worker-focused modules, industrial plants also appear as complex incident settings for operational response training: Wu and Liu [24] propose a 3D simulation-based fire-rescue training system that combines rescue path planning and risk assessment, and evaluates performance across scenarios including factory fires and chemical-plant fires (alongside other complex built environments).

Taken together, these industrial applications show how XR technologies are used less to reproduce large territorial networks than to expose and manipulate the fine - grained coupling between spatial layouts, equipment configurations and safety procedures in dense technical environments, complementing the large-scale, systems-oriented focus observed in the energy domain.

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. 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.

Beyond their technical function, these infrastructures illustrate a new dimension of resilience: informational resilience, 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.

4.4.6. Healthcare Infrastructures

Healthcare facilities represent one of the most intricate and interdependent categories of critical infrastructure, where spatial configuration, service continuity, and operational interconnection directly influence system performance during emergencies. The case of Auckland City Hospital (ACH), the New Zealand's largest public hospital and clinical research facility [95, 111], illustrates these dynamics particularly well, serving as a paradigmatic example of how large-scale healthcare systems behave under seismic stress. Selected for its operational complexity, high occupant density, and the essential nature of its functions, the hospital provides an ideal testbed for immersive training technologies aimed at operational resilience and emergency management. The facility consists of a multi-building complex that integrates clinical wards, diagnostic and surgical units, administrative offices, and public areas such as corridors, lobbies, and waiting rooms. These spaces are connected through a dense network of vertical and horizontal circulation routes, forming overlapping zones of access, movement, and responsibility. Within this intricate layout, staff, patients, and visitors share partially intersecting pathways, revealing the dual identity of hospitals as both care environments and logistical systems, where controlled circulation and open accessibility must constantly coexist. From an infrastructural perspective, ACH demonstrates how functional dependencies, for instance, between emergency exits, lift systems, and intensive care units, become critical under disruptive conditions. Its compact morphology and high occupancy increase the facility's exposure to non-structural damage, while its complex internal connectivity influences both the propagation of risk and the efficiency of evacuation strategies. As a simulated environment, Auckland City Hospital thus represents an invaluable spatial and organizational model for analyzing the resilience of healthcare infrastructures, highlighting how architectural form and functional inter-dependence shape performance during seismic and multi - hazard events. Complementarily, the study in [46] shifts the focus to a rural healthcare system, modelling it parametrically as an acute-care rural hospital (e.g., number of physicians and nurses, triage rooms, ER beds, and inpatient wards), while also integrating public-health and emergency-management subsystems; in this case, the main response variable is the overall performance of the healthcare/hospital system. Moreover, the adopted approach underscores the potential of VR for interdisciplinary training, integrating medical, technical, and administrative perspectives within the same virtual ecosystem.

Healthcare infrastructures exemplify how immersive technologies can bridge technical, organizational, and human factors, transforming complex service networks into living laboratories of resilience. Their methodological insights, on interdependence, redundancy, and coordinated evacuation, resonate across other infrastructural domains, from communication to education and urban system.

4.4.7. Workplace and office environments

In office environments, immersive technologies are increasingly used to reconcile operational continuity and safety training, turning the workplace into a laboratory for organizational and behavioral resilience. In this context, office environments represent a distinct yet increasingly relevant subset of critical and organizational infrastructures. Though less exposed to physical hazards than industrial or transport systems, offices concentrate human presence, digital assets, and service continuity dependencies that make them critical for institutional and corporate resilience. Immersive and simulation-based applications in this domain address primarily evacuation dynamics, behavioral adaptation, and cognitive responses to emergency cues. Several studies reproduce multi-floor office layouts and dense occupancy conditions to evaluate route selection, decision-making under alarm, and adherence to safety instructions, highlighting how cognitive load and spatial familiarity affect evacuation performance. Scenarios typically include fire, smoke propagation, and earthquake evacuation [54, 107, 113], focusing on spatial perception, stress management, and the communication of real-time alerts. More recent work deploys optical see-through AR systems directly in office corridors and circulation spaces to train building occupants in key fire-safety tasks and compares the effectiveness of this training with conventional video-based methods [110].

Beyond physical evacuation, some works expand toward organizational resilience and human-factor assessment, linking safety training with workplace well-being, ergonomic design, and psychological readiness.

4.4.8. Educational infrastructures

Educational facilities – in particular schools and universities – constitute a distinct class of critical infrastructure where safety management and knowledge dissemination converge.

Across the literature, AR and mobile-AR tools overlay geological or meteorological content onto textbooks, classroom walls or outdoor areas [78; 79; 43; 45; 80], turning ordinary lessons into situated explorations of risk while retaining the school building as a fixed spatial frame [78; 79; 43; 45; 80]. Other studies use school layouts, timetables and assembly areas as the backbone of evacuation drills and preparedness modules, pairing physical exercises or metaverse sessions with simulation outputs to help students and staff understand circulation patterns, bottlenecks and waiting zones [123; 72].

In educational settings, studies converge on the idea of using immersive environments to turn schools and campuses into true laboratories for emergency preparedness, while still adopting different technological and pedagogical approaches.

In public schools and primary education, virtual reality serious games reproduce typical school layouts and codified fire regulations, training pupils and teachers in evacuation procedures and emergency management through narratively structured scenarios [84, 94]. At university level, virtual replicas of teaching and laboratory buildings – including campus-scale virtual worlds and metaverse-based evacuation systems – allow the repetition of fire drills and the testing of dynamic guidance strategies under realistic occupancy conditions [23, 48, 87]. More infrastructural approaches combine digital twins of training towers and classroom blocks, multi-user preparedness platforms and VR games integrated into learning-management systems, engaging students, teachers and safety professionals in shared preparedness scenarios that can be monitored and adapted over time [65, 115, 116, 121].

These experiences demonstrate how schools can function as learning-critical infrastructures, spaces where architectural design, organizational routines and educational objectives align to promote a culture of preparedness. Evidence from controlled studies further indicates that VR-based fire safety programmes can strengthen knowledge of safety measures and individual awareness among students and academic staff, supporting the long-term internalization of emergency procedures [102]. Immersive technologies extend this paradigm, turning the very act of learning into a resilience-building process that links personal awareness, institutional readiness and community safety.

4.4.9. Urban environment

Urban and territorial infrastructures occupy a central position in resilience strategies, as cities concentrate critical assets, services, and populations within interdependent systems of transport, housing, and lifelines.

Overall, the case studies reviewed delineate a continuum of urban configurations and roles: from synthetic and regional city models developed for seismic and multi-hazard scenarios [18, 19, 42, 52, 53, 67], to representations of coasts, river corridors and neighbourhoods exposed to hydro-meteorological and coastal events [99, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96], up to XR frameworks and collaborative virtual reality environments that stage floods, compound disasters and large metropolitan emergencies [47, 56, 66, 91], while at a more local scale serious games and training systems focus the interventions of emergency services on urban buildings and public spaces [20, 21, 82, 85] and on infrastructure construction sites [33, 83].

Several studies, particularly those addressing seismic applications [18, 19, 42, 52, 53, 67], explore how immersive and simulation-based environments can represent, analyse and teach the interconnections between built form, hazard dynamics and human behaviour under emergency conditions. These contributions highlight the role of spatial, organisational and social factors in shaping collective response and recovery.

Early contributions, such as Zhou et al [67], operate at a regional scale, generating virtual cities composed of administrative areas, industrial districts, residential zones, and lifeline systems, including hospitals, schools, and emergency shelters. These synthetic environments are designed to train public officials in decision-making and inter-agency coordination, simulating large-scale earthquakes and their cascading effects on critical infrastructures. Building on this framework, [19] (Tian et al., 2018) refines the model into a parametric three-dimensional city, combining topography, vegetation, and street furniture to create a flexible and photorealistic environment. The system allows users to modify morphological and environmental parameters dynamically, tailoring simulation scenarios to specific local conditions and enabling cross-scenario comparisons for planning and response strategies.

Later immersive applications, such as VRescuer [42] and VRescue [52], shift the focus to collapsed and damaged cityscapes, enabling participants to navigate debris-filled streets and ruined structures during post-earthquake operations. In VRescue [52], Carrozzino et al. reconstruct a historic Italian city center through high-resolution photogrammetry and Unity-based physics simulation.

A complementary perspective is offered by De Fino et al. [53], who reintroduce open urban space as a key component of emergency management, focusing on public squares as social and logistical nodes during crises and employing Built Environment Typologies (BETs) to represent characteristic configurations of Italian urban morphology. By parameterising architectural form, spatial configuration and functional characteristics, BETs provide a structured and replicable framework for simulating multi-hazard conditions in typified public spaces and, in the prototype developed within the BE S2ECURE project, help to redefine these spaces not as simple static civic amenities but as functional components of the city's resilience infrastructure. Compared to indoor environments, outdoor spaces – whether used as primary training scenarios or as safe assembly areas at the end of indoor drills – are generally more simplified and schematic, due to their spatial complexity and scale [53], yet this abstraction is anchored in taxonomic assessments of real-world cases, which ensure a balance between realism and manageability. Through BETs [144, 145], public spaces thus become parametric learning environments in which urban form and emergency function are aligned within the same educational framework.

In parallel with seismic applications, numerous contributions broaden this perspective to include other hazards, particularly hydro-meteorological and coastal events, framing the urban environment as an interconnected system of streets, blocks, open spaces and key sites that must remain functional under different stresses [14, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96]. VR, desktop and XR tools that represent coastal towns, river corridors and slope-side settlements use building clusters, road hierarchies and critical nodes such as squares or bridges as the main objects of exploration, encouraging learners to reason about accessibility, exposure and continuity of essential services at the neighbourhood scale [99, 36, 100, 98, 69, 70, 40, 41, 25, 37, 38, 56, 96].

Within this framework, the literature documents several cases in which specific existing urban contexts are modelled as immersive multi-hazard training scenarios. The historic centre and river corridor of Senigallia [56] are used to construct an extended reality framework that combines reusable typological scenarios and site-specific environments, with the aim of training citizens, technicians and decision-makers in flood-risk management and related civil protection measures. Within a multidisciplinary “dual hackathon” [66], the same type of flood-affected territory is employed as a testbed for coordinating engineering expertise, risk communication and operational decisions during a joint exercise involving universities and local authorities. A similar approach underpins the experiential training system MisasTer [91], which places participants in a coastal city subject to a sequence of earthquake, tsunami and fire, drawing on the official disaster-prevention map to structure realistic evacuation routes and assess the correct use of escape paths. At an even larger scale, the collaborative Megacity environment [47] represents a complex metropolitan area in virtual reality, in which multi-user teams can explore different crisis scenarios, test alternative strategies and observe how choices affecting individual assets ripple through interdependent infra-structure networks.

Participatory simulations further extend this vision at the urban scale, allowing groups of residents, students or decision-makers to modify measures such as local protection works, land-use options or emergency routes and to observe how these changes propagate through the urban fabric [124, 39, 125]. In these implementations, the urban environment is treated as a multi-level critical infrastructure in which built form, circulation and institutional decisions jointly determine resilience.

At an intermediate scale between the neighborhood and the individual public space, several serious games and training systems take the urban building and its immediate surroundings as the operational unit, alternating the perspective of emergency services with that of occupants. The serious game Fireman Rescue [85] places the player in the role of a firefighter responding to everyday urban scenarios – a burning waste container, a vehicle fire, a dwelling with victims to evacuate – and assesses the ability to follow operational protocols, select access routes and correctly use equipment and protective devices under pressure. Complementarily, the VR-based training system [20] proposes indoor scenarios set in typically urban facilities such as shopping centers and hospitals, highlighting how the distributive complexity of corridors, atria, wards and retail areas affects evacuation times and modes and fire-attack strategies.

On the side of occupants and egress management, the training model [21] 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 [82] 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.

In the same urban environment, several serious games and training modules bring flood- and water-protection systems to the foreground as infrastructures in their own right. VR and desktop scenarios model levees, mobile barriers, pumps, temporary protection units and drainage elements as manipulable components, asking learners to design or deploy configurations that protect streets, buildings and key functions under resource and time constraints [101, 73]. Data-driven and digital-twin platforms link hydrological behavior at catchment scale with local assets such as embankments, channels or sensor-equipped sites, making it possible to visualize how interventions on individual structures transform conditions at neighborhood scale [25]. In this perspective, protection systems are no longer passive background elements, but critical infrastructures that mediate the relationship between urban form and external stressors.

Finally, although they do not directly address the neighborhood scale, VR applications dedicated to safety in excavations [33] and in geotechnical drilling works [83] draw attention to an often overlooked dimension of the urban environment: that of construction sites and infrastructures under construction, where trenches, underground utilities and machinery in turn become critical risk nodes and must be considered within the broader framework of built-environment resilience. Complementarily, some VR-based safety-training studies address cross-cutting high-risk tasks such as con-fined-space entry, comparing a productive-failure instructional design with a directive-instruction approach to develop declarative knowledge on the selection

of safety equipment, within a confined-space scenario modelled on an actual sewage-dredging work site [32].

Taken together, these contributions present the urban built environment as a dynamic ecosystem in which digital modelling, immersive simulation and resilience pedagogy converge to foster systemic understanding. Whether addressing seismic or hydrological risks, these environments enable professionals, students and citizens to experiment with spatial configurations, cascading hazards and collective decision-making processes under stress. By integrating the logics of interdependence, adaptability and co-production within urban training frameworks, immersive simulations turn the city into a pedagogical instrument capable of cultivating the situational awareness and collaborative intelligence required by contemporary resilience governance.

4.5. Actors and stakeholders

The segmentation of stakeholders across the reviewed contributions reflects the growing ambition to make education technologies a cross-cutting formative approach, capable of engaging participants at different levels of competence, responsibility, and operational risk.

Within the analyzed literature, two main design logics can be observed. As shown in Figure 19, the reviewed corpus spans multiple actor categories, with Technical Workers and Process Operators emerging as the most represented group (35%), further detailed into Process and Plant Operators (13%), Field technicians and specialist workers (12%), and Technical Operators in Transport Systems (10%).

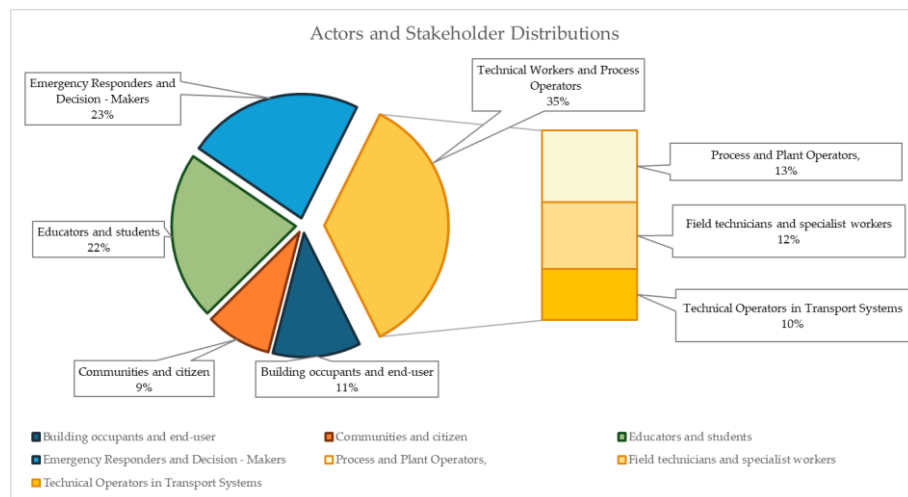


Figure 18: Actors and stakeholder distributions across the reviewed studies, including a detailed breakdown of the Technical Workers and Process Operators cluster. Image created by the authors.

Some studies start from the critical infrastructure itself [95, 107, 111], identifying the various categories of occupants and functional roles within it, such as operators, visitors, maintenance staff, and process managers. Others develop experiences tailored to specific user typologies [18, 52, 42, 54, 97, 112, 113], including rescuers, technical workers, or students. This dual perspective highlights how immersive technology support the mapping of human complexity within infrastructural systems, enabling an educational continuum that spans from the asset management workforce to the individual citizen. Within the hazard-focused subset, this dual logic reappears with different emphases. A large group of applications places school and university learners at the centre, embedding geohazards and hydrological risks into curricular activities or laboratory - style tasks [25, 36, 37, 40, 41, 43, 45, 73, 78, 79, 80, 99, 100, 123]. Others design participatory simulations and training frameworks that bring together residents, teachers, scientists, civil protection officers, and emergency responders in shared flood, landslide, tsunamis, or

hurricane scenarios, so that evacuees, planners, and crisis managers act in the same digital environment from distinct role perspectives [25, 38, 39, 56, 66, 69, 70, 71, 72, 74, 121, 124, 125]. These contributions extend stakeholder mapping beyond single institutions and tie education technologies explicitly 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 [57].

4.5.1. Emergency Responders and Decision-Makers

In the domain of crisis and emergency management [108], immersive simulations address a wide spectrum of professional profiles, ranging from operational responders in the field to institutional and strategic decision-makers. Together, these groups represent the backbone of emergency preparedness: one responsible for tactical execution under stress, the other for coordination and decision-making across organizational levels.

At the operational level, *VRRescue* [52] was specifically developed for Urban Search and Rescue (USAR) teams, enabling them to practice tactical and procedural decision-making in photorealistic post-disaster environments. These simulations combine physical realism and behavioral assessment, requiring participants to perform tasks such as navigation through debris, triage of victims, and use of professional equipment (GPS, dosimeters, radios). Beyond USAR-specific tools, several VR-based firefighting systems adopt similar logics for building and urban emergencies. A BIM-based virtual training environment [82] links information models of complex facilities such as airports and stations with simulated fires, smoke and explosions, so that fire crews can rehearse rapid orientation, team coordination and equipment handling in high-risk buildings. A multi-scenario training system [20] exposes participants to four typical fire contexts – shopping mall, hospital, dwelling and entertainment venue – where they must move through smoke, operate extinguishers, hydrants and fire doors, and manage lifts and escape routes. The serious game *Fireman Rescue* [85], designed for firefighter education, similarly places trainees in everyday urban emergency situations while recording actions, errors and timings to support debriefing and targeted feedback. Through iterative practice, trainees improve coordination, reaction time, and situational awareness, developing cognitive flexibility under stress.

Similarly, multi-role simulations like *FrèjusVR* [57, 58] involve distinct participant roles (firefighters, civilians, and truck drivers, who must collaborate, maintain safe distances) or trigger emergency procedures, linking individual behavior to collective safety. In parallel, the *HCP-VR system* [55] addresses hydrogeological emergencies, enabling Civil Protection responders to rehearse high-capacity pumping operations in flooded environments through guided and evaluated modes that integrate procedural instruction, safety protocols, and performance assessment. Within the same trajectory, the *EGCERSIS* platform [108] extends this logic to coordinated multi-actor response in transport environments, using a metro-station digital twin where firefighters, police, and medical teams operate under a shared decision-support system to rehearse complex emergency management workflows. A similar integration of sensing, monitoring and virtual environments is pursued by the *GUIDE2FR platform* [65], which couples a digital twin of a firefighter training tower and nearby buildings with robust wireless beacons, cloud-based data management and predictive air-quality models to support first responders and control-room operators during emergency exercises.

At the strategic level, a web-based tabletop system was developed to support decision-makers in managing command structures, inter-agency communication, and resource allocation during large-scale seismic events [67]. The environment reproduces hierarchical coordination, information exchange, and policy formulation processes, fostering collaborative reasoning and evidence-based decision-making. In a different sector, a proof-of-concept multi-method computer simulation for rural healthcare disaster preparedness [46] combines system-dynamics and discrete-event modelling to represent patient flows, capacities and triage processes, allowing health planners and emergency managers to evaluate how alternative preparedness policies and resource configurations affect service performance under catastrophic scenarios.

Among the most advanced implementations, the *VRRescue* training system, tested at the USAR Center in Pisa [52], exemplifies how immersive simulations are now being incorporated into institutional firefighter-

training programs. Similarly, *Fireman Rescue* [85] and *GUIDE2FR* [65] are now embedded in stable training facilities and programmes for fire brigades and civil protection services. Overall, these initiatives highlight the shift from experimental prototypes to permanent training infrastructures and signal the progressive integration of virtual reality and digital-twin technologies into official emergency-preparedness curricula.

Within the hazard - focused corpus, several systems target responders and crisis managers in transport and territorial settings. *Tunnel VR* training integrates BIM-based incidents so trainees practice lane closures, traffic control, and occupant guidance under fire and smoke [28], while mixed - reality ADR tanker scenarios use HoloLens overlays to rehearse stabilization, hazard identification, and first aid with logged procedural performance [77]. *HurricaneLog* captures how humanitarian logisticians and emergency managers plan stocks, shelters, and fleets under hurricane uncertainty [74], and *Flood Action VR* stages multi - phase flood missions for emergency services and volunteers, assessed mainly through usability and perceived preparedness [38].

At the institutional level, volcanic - unrest exercises convene scientists and civil protection officials around probabilistic BET_UNREST outputs [71], participatory flood simulations engage municipal staff and elected representatives on urban and coastal prevention portfolios [124; 39; 125], and tsunami evacuation planning links inundation models with school drills so teachers and local authorities jointly revise routes and assembly points [72]. XR frameworks extend this logic conceptually to multi - profile urban risk training, though implemented pilots remain limited [56].

Furthermore, across multi - environment settings, the use of VR reveals communication bottlenecks between control rooms and field operators, detects stress even among experienced personnel, and shows improvements in response times after just a few iterations. In parallel, data - driven solutions such as PSO - assisted routing and dynamic risk assessment support responders in complex scenarios, such as high - rise buildings or industrial plants, increasing efficiency and safety during fires and chemical releases [24]. To make this qualitative leap in training sustainable, and to close the gap between what is learned and what is done for these stakeholders, the evidence must be strengthened through longitudinal evaluations of real - world performance, outcome metrics beyond usability, and simulators designed to be age - inclusive and team - aware.

Taken together, these applications bridge the operational and institutional dimensions of emergency management, aligning tactical execution and strategic coordination within a shared digital ecosystem.

4.5.2. Technical Workers and Process Operators

Technical workers and process operators constitute the operational backbone of many critical infrastructures, particularly in industrial, energy, transport and protection systems. Within the reviewed corpus, these profiles can be interpreted through three recurring operational groupings: (i) process and plant operators, including plant and maintenance technicians, substation controllers, and – within the maritime domain – engine-room personnel, responsible for running and maintaining process assets and safety-critical equipment; (ii) field technicians and specialist workers, such as field operators and movable flood-barrier operators, who perform mobile tasks at the interface between infrastructure and its surrounding environment; and (iii) technical operators in transport systems, including locomotive crews and other railway technical staff, as well as tunnel controllers, who manage procedures and coordination in moving or spatially constrained contexts. Across all three groupings, daily activities directly mediate between complex socio-technical systems and material processes, meaning that errors may rapidly escalate into major incidents and that routine tasks are frequently carried out under tight temporal, procedural, and safety constraints, as well as under high levels of operational stress. Besides routine operations, several applications explicitly target emergency readiness through drill-like modules that rehearse recognition, response sequencing and evacuation under time pressure [102, 115], including multi-hazard drill logics where earthquake dynamics cascade into subsequent threats that must be managed within a single training flow [91].

Within the analyzed corpus, immersive training is employed to make explicit the coupling between spatial configuration, process logics and standard operating procedures, enabling these workers to rehearse

complex workflows, hazard scenarios and coordination patterns in controlled yet realistic environments. The main objectives are to improve procedural accuracy and safety performance, to strengthen operational coordination with co-workers, control rooms and emergency teams, and to develop skills for managing stress under abnormal or emergency conditions. In parallel, some contributions incorporate data layers and performance metrics (e.g., timing, errors, and behavioral indicators) to support scenario analytics and after-action review, thereby bridging procedural rehearsal with decision-support and preparedness evaluation [56, 121, 108].

In industrial and energy-related infrastructures, VR is widely used to support complex task training along the process chain. Evidence from the oil and gas and industrial-production domains [26, 30, 92, 106] shows that immersive environments are deployed for plant inspection and anomaly detection, commissioning and calibration tasks, emergency routines, and other high-consequence operations, reducing exposure to real hazards while minimizing costly operational errors and unsafe acts. Maintenance safety training is also reported through VR modules for plant maintenance procedures [88]. Comparable procedure-centric logics are reported for power-supply operations, where immersive modules train switching and testing routines for electric-power operation employees [31] and support periodic training for substation service personnel and on-duty operators [89], including offshore or high-risk configurations where procedural compliance and safety awareness are critical [26]. In parallel, targeted implementations focus on isolation and lockout sequences for low-voltage systems among operators, electrical specialists and operational HSE roles across industrial and utility settings [117], while emergency-oriented simulators extend training to the coordinated rescue actions of electric power field operators during incidents in distribution environments [22]. A closely related strand addresses safety training in automated production facilities, where VR makes interlocks, exclusion zones and stop conditions observable and testable, improving operator readiness when working near robots or semi-autonomous equipment [105]. Comparable emergency-preparedness patterns are also reported for underground and constrained industrial settings, where rare but high-consequence events (e.g., mine incidents) can be rehearsed without exposing workers to real harm [93]. A similar logic applies to process and utility technicians working in confined spaces, where dedicated IVR platforms [60, 32] treat tanks, silos, underground chambers and manholes as critical sub-infrastructures. These systems guide operators through step-by-step procedures for entry, work and rescue, and explicitly model how geometric configuration, atmospheric conditions and equipment layout define safe and unsafe margins; in addition, they foreground pre-entry preparation by training workers to select appropriate protective equipment and tools before entering the space [32], thereby reducing procedural errors even among trainees with prior formal safety instruction [60]. For hydropower plant operators, immersive training leverages a computational platform for a 132 MW facility [64] to let technicians rehearse operational commands and abnormal procedures under controlled conditions. Within this setting, the machine hall, control room, and access routes are virtualized as task-relevant workspaces, while the simulated plant behavior supports the development of resilience-oriented competences – decision-making, coordination, and constraint management – during grid disturbances and equipment faults. In some implementations, motion-tracking systems and treadmill-based locomotion modules are introduced to replicate operational stress and enhance ergonomic awareness, with the aim of improving both immersion and learning transfer. Related emergency-preparedness drills are also reported for gas-powered plant contexts, where trainees rehearse evacuation and mitigation actions aligned with occupational safety frameworks and standardized safety management principles [103].

A second group of applications targets mobile and specialist technical staff who operate at the interface between infrastructures and their surrounding environment. Within corporate and chemical laboratory settings, VR serious games [118] and inspection environments [75] have been shown to increase attentional absorption and motivation among laboratory staff, safety personnel and compliance actors, encouraging gradual integration with traditional training methods, particularly for senior operators who may be less familiar with game-based interfaces. Importantly, these tools are not limited to generic student audiences: some systems are explicitly designed for operational safety roles, such as Safety and Health Coordinators and laboratory inspectors responsible for periodic inspections and compliance across heterogeneous research facilities [75]. Beyond laboratories, operator-centered VR training is applied to high-risk worksites in which hazards emerge from the interaction of workers, machinery and evolving site configurations. In construction, excavation and roadwork contexts, immersive scenarios train workers to identify, evaluate and respond to hazards on real jobsite layouts [33, 51], and data-structured approaches further encode hazard zones and replay worksite dynamics to improve traceability of unsafe proximities and procedural

deviations during training [68]. Comparable logics recur in geotechnical drilling worksites, where simulations are built around the coordinated actions of drillers and assistants near heavy machinery [83, 104], and in open-pit quarrying, where workers and H&S trainers rehearse safe practices under rapidly changing, equipment-dense conditions [59]. A parallel strand focuses on electrical and maintenance trades, from active construction sites [109] to at-risk technical occupations including wind-turbine service and crane/tower operations [50], where training emphasizes procedural safety, work-at-height constraints and isolation discipline. In PV façade operations, gamified scenarios similarly foreground lockout–tagout routines and role-specific decision-making for cleaning, maintenance and repair personnel [29]. In protection services, immersive environments further extend operator-centered training to structured intervention and coordination tasks, ranging from firefighter operations rehearsed in virtualized building scenarios to complex multi-actor emergency situations that foreground rapid decision-making and role allocation [82, 85]. More marginally, some safety programs also connect operator training ecosystems with risk communication measures aimed at infrastructure users, such as behavioral education to reduce accidents at critical points (e.g., pedestrians in hazardous areas) [86].

In mobility infrastructures, technical personnel must manage systems in motion while safeguarding passengers, freight and crew. For railway personnel, VR-based fire safety training in passenger trains [119] allows drivers and onboard staff to rehearse the management of onboard fires and evacuations in a virtual vehicle interior, reporting high perceived realism and usability, along with improved understanding of operational sequences and crew–passenger interactions. In this context, other studies focus on VR training for locomotive crew [35], combining emergency drills, diagnostic simulation and automated assessment to enhance procedural competence and safety management. Beyond vehicles, tunnel contexts provide a salient example of socio-technical coordination between users, control-room staff, and responders: immersive environments can be used both to rehearse user-side decisions in constrained evacuation conditions and to train intervention teams operating under smoke, limited visibility and evolving hazards, including multi-actor tunnel-fire scenarios [57, 58] and role-differentiated highway-tunnel response platforms spanning control-room operators, emergency teams, and road users [28]. Related transport-oriented systems also explore decision-support configurations at station scale, where digital-twin cores ingest evolving state variables and user actions to support real-time reasoning and operational choices during crisis exercises [108]. Comparable behavioral frameworks have additionally been extended to intentional crisis scenarios through interactive designs that simulate deliberate attacks, broadening preparedness training beyond accidental events [61].

In the maritime domain, the reviewed studies converge on training aimed at shipboard technical operators, with different emphases depending on the operational context. For mooring operations, individual VR training prioritizes dynamic risk assessment and shows favorable outcomes compared to classroom instruction [114]. In the engine room, to reduce procedural ambiguity, a platform combining initial tutorials, virtual guidance and just-in-time feedback supports technical staff and maritime engineers in executing maintenance and safety checklists [122]. For high-voltage shipboard electrical systems, a dedicated simulator promotes safe procedures and behaviors in high electrical-risk scenarios [120]. Fire preparedness is likewise addressed through drill-oriented VR modules aligned with seafarer certification routines, enabling crews to rehearse detection, initial response and evacuation sequences under constrained onboard conditions [110, 126]. In aviation, immersive training targets both pre-flight technical inspection roles and emergency decision-making for operational trainees, extending procedural competence to high-stress, time-constrained scenarios [27, 90]. Across these transport examples, immersive environments help operators internalize standardized procedures and practice real-time decision-making in situations that would be difficult or dangerous to recreate in the field.



Figure 19: VR instructions on how to handle the most common faults in a locomotive for crew training. Reproduced from [35], © 2023 The Author(s), distributed under the Creative Commons Attribution License (CC BY 4.0).

Across these strands, studies consistently report higher situational awareness, improved adherence to safety protocols and increased cognitive readiness among technical workers and process operators who train in immersive environments. At the same time, key limitations persist: evaluations often rely on small convenience samples, long-term workplace validation remains scarce, and outcomes frequently focus on usability or short-term learning rather than operational performance. Implementation barriers also include integrating VR into mandatory safety curricula, keeping models aligned with evolving assets and procedures, and ensuring acceptance among experienced workers. Nevertheless, when embedded in existing training ecosystems, immersive applications can bridge complex socio-technical systems and everyday practice, supporting both vertical adaptability across expertise levels and horizontal coordination between field staff, control rooms, and emergency teams.

4.5.3. Building occupants and end-user

Building occupants constitute one of the most heterogeneous and behaviorally influential stakeholder groups within the context of critical infrastructures. They include individuals who work, study, or transit in public buildings such as hospitals, office complexes, and schools. Their actions during emergencies depend on a complex interaction between spatial configuration, functional hierarchies, and individual preparedness, which determines how they perceive risks, interpret cues, and make decisions under stress. Training these users, professionals and non-specialists alike, is essential to ensure both individual safety and collective coordination within complex facilities.

Across the reviewed corpus, two complementary strands emerge: (i) behavioral research using immersive environments to observe and measure occupant responses under controlled conditions; and (ii) training applications, designed to teach and reinforce correct responses and translate simulated experience into preparedness.

The behavioral dimension is exemplified by Lovreglio et al. [95], who reconstruct a seismic scenario in a section of the Auckland City Hospital through VR and BIM to study occupant decision-making. Healthcare facilities are particularly insightful case studies because they combine diverse occupant typologies – doctors, nurses, administrative personnel, and visitors – whose movement patterns and priorities differ sharply. Participants experienced shaking, visual obstruction, and falling debris, allowing researchers to measure evacuation choices and reaction times in a controlled yet realistic setting. This study positions VR as a behavioral observatory, capable of producing empirical data on human responses that inform both emergency planning and architectural design. Building on this foundation, an immersive serious game using the same hospital model was developed [95, 111], shifting the focus from observation to training and preparedness. Here, users actively performed safety actions, such as protective actions (e.g., “drop, hide, cover”), hazard identification and safe route selection, while receiving immediate feedback on their performance. This approach demonstrated how immersive learning strengthens self-efficacy and procedural awareness, showing that VR can serve as a unifying platform for both professional training and public

preparedness within the same infrastructural ecosystem. Similarly, in confined transit infrastructures, the multi-user road-tunnel fire simulator *FréjusVR* [57, 58] trains civilian end-users to rehearse protective actions and evacuation choices under smoke and time pressure; within the same training setting, the impact of avatar representation indicates that switching from “VR-kit-only” proxies to full-body reconstructions affects immersion and social-presence dimensions and is generally preferred for representing the other user during multi-player interactions.

A customizable framework extending this logic to other building types, including offices and administrative complexes, was developed by Feng et al. [107], confirming the scalability of immersive simulations across contexts. At the architectural level, an extensible VR emergency-preparedness framework [116] is proposed as an architecture that can be adapted across scenarios and locations (e.g., workplaces and commercial buildings) to complement conventional drills and scale occupant preparedness. In particular, iterative narrative design (spiral storytelling) encourages reflection and correction in office-based evacuation drills, reinforcing long-term behavioral retention [113].

In educational infrastructures, immersive and mobile VR are applied to simulate emergency scenarios in classrooms and corridors, training teachers and students in evacuation preparedness for earthquake [97, 112] or fire [23, 48, 87, 116]. Complementarily, a VR-based fire-evacuation training model [21] formalizes route safety through an optimal escape-path formulation based on survivability constraints under high temperatures and harmful gases, using it to compare evacuees' choices against safer alternatives and provide feedback. Beyond VR, optical see-through AR fire-safety training for building occupants [76] has been compared against video instruction, showing comparable knowledge acquisition and retention while yielding higher intrinsic-motivation gains and better self-efficacy retention. The experiments show that VR-based exercises produce significant improvements in knowledge retention and behavioral readiness, outperforming traditional paper-based instruction. In online settings, the *Virtual Safety World* [48] delivers knowledge gains comparable to slide-based training while increasing engagement (participants voluntarily spend more time in training), improving one-month retention, and sustaining attention through instrument-based measures. In parallel, Nilsen et al. [18] explored the influence of game mechanics, such as resource richness and avatar customization, on motivation and concentration during serious-game-based learning, while Rahouti et al. [54] introduced adaptive algorithms to dynamically adjust task difficulty and feedback. In the same adaptive direction, metaverse-based building-evacuation training that updates guidance based on real-time information (e.g., crowd distribution and disaster location) outperforms static guidance in evacuation-time savings [23].

Several contributions extend occupant analysis to residential and mixed-use settings under hydro-meteorological hazards. Interactive landslide simulators place users as householders choosing structural and behavioral measures while a simple model shows whether a landslide occurs and how severe it is, allowing analysis of how feedback timing and context shape risk judgements and mitigation preferences [69, 70]. A flood-risk simulation casts learners as floodplain residents who compare protection levels and land-use options, justifying their assessments, focusing on how they construct geohazard arguments [40]. Urban-scale tools built from 360-degree panoramas simulate city-center evacuations and sheltering, recording route choices and times under varied layouts [96], while flood and tsunami preparedness games ask inhabitants of low-lying neighborhoods to identify safe routes, decide when to leave, or allocate limited resources, turning occupant decisions into both training targets and behavioral data [41, 37, 73].

4.5.4. Educators and students

While building occupants engage with immersive technologies primarily as users of infrastructures, educators and students represent a second, distinct stakeholder group: they are learners and knowledge multipliers, central to the diffusion of a safety - oriented culture. In this cluster, immersive technologies serve not only as emergency preparedness tools but also as pedagogical frameworks for shaping the next generation of engineers, architects, and professionals equipped to manage complex systems under risk.

A growing number of studies explore VR and SGs as tools for cognitive empowerment within educational settings, promoting both awareness and professional competence. At the school level, Sukirman et al. [97] developed a mobile VR application for secondary-school students in Indonesia, accessible through low - cost devices such as Google Cardboard. The system trained users in self - evacuation procedures during earthquakes, achieving a 71% improvement in behavioral preparedness and confirming the effectiveness of

mobile VR as a low-cost platform for preventive education and experiential learning. Along the same line, serious games developed for public schools [84] enable pupils to rehearse escape routes and behavioral choices in virtual replicas of their school buildings, consolidating basic rules – use of emergency exits, compliance with signage, avoidance of lifts and hazardous areas – before physical drills. VR-based fire-safety training studies similarly indicate that, even in secondary and technical education, exposure to immersive scenarios can increase individual awareness and perceived self-efficacy in dealing with incipient fires.

Building on this line of research, Feng et al. [112] designed an immersive serious game for a junior secondary school in Australasia, developed through a BIM-Unity workflow and implemented on Oculus Rift. The game simulated an indoor earthquake and post-evacuation scenarios from a first-person perspective, enabling students aged 11-15 to practice realistic responses under stress. The experiment compared three instructional approaches - prior instruction, immediate feedback, and post-game assessment, against a control group trained with leaflets. Results revealed that the post - game assessment condition was the most effective for training children, with greater knowledge acquisition and improved self-efficacy observed [112]. The authors highlighted that IVR SGs help children reflect on their previous behaviors against the feedback they were taking, enhancing retention through a second exposure brought by post - game assessment [112]. An important insight concerns the role of teachers as active facilitators in the learning process [97, 91]. The same platform was used to train educators to guide students during emergency drills, highlighting that immersive simulations not only teach correct actions but also train teachers in leadership, coordination, and risk communication. By enabling instructors to experience and manage virtual emergencies, these tools strengthen the pedagogical dimension of resilience education and empower teachers as mediators between technology and student learning. Complementarily, *FSCHOOL* [94], evaluated with primary-school teachers, shows that VR can be used not only to train pupils but also to strengthen the role of teachers as first safety responsible in the classroom: simulations of prevention, initial extinguishing and evacuation improve procedural knowledge, confidence in their own abilities and motivation to lead students during emergencies. At university level, the *Fire Evacuation Game* [115] likewise confirms the interest of students, academic staff and fire-safety services in gamified evacuation-preparedness formats, while teacher and practitioner evaluations highlight the need for technical support and clear integration with existing learning platforms and emergency plans if such tools are to become a stable component of educational practice rather than isolated experiences.

Hazard-focused applications in schools follow a similar logic while widening the scope to geoscience and hydrometeorological risks. *Volcanology AR* atlases convert static diagrams into interactive 3D models that pupils rotate on mobile devices, with worksheets framing discussion of eruption styles and associated threats [78; 79]. Tropical cyclone and tornado simulators combine handheld AR, desktop visualization, and mixed reality so students can manipulate storm parameters and link changes in track and intensity to learning goals on atmospheric processes and warnings [43; 45; 8]. Tsunami and coastal-flood simulations embed local topography and landmarks into virtual environments so classes walk through inundation in recognizable spaces, strengthening links between concepts, place - based knowledge, and drills [100; 37]. Teachers introduce and debrief these tools, while evaluations address knowledge, interest, and self-efficacy.

In higher education, immersive simulations are increasingly integrated into engineering and safety curricula, fostering professional and analytical competence. Within this context, the spiral - narrative framework developed by Feng et al. [113] was applied to university staff and students, demonstrating how iterative exposure to VR scenarios promotes reflection-in-action, adaptive reasoning, and durable knowledge retention. Through this design, scenarios could be repeated and reflectively re-experienced, allowing learners to adjust their responses based on in - game feedback. The study concluded that immersive serious games can deliver knowledge and enhance self-efficacy as effectively as traditional approaches while offering greater emotional engagement and long - term retention potential. In higher-education programmes, immersive technologies are also used to engage students in tasks that closely resemble professional practice. In engineering and construction courses, multi-device platforms for highway work-zone safety [49] allow students to explore complex sites, recognise hazards and translate their observations into technical reports and formal risk documentation. In experiences such as the “dual hackathon” on flood scenarios [66], students take on quasi-professional roles – designers, risk analysts, coordinators – and, under the guidance of lecturers and tutors, negotiate solutions together with engineers and civil-protection representatives. In these contexts, XR environments do not simply “show” the effects of an extreme event,

but become testbeds for making decisions, comparing perspectives and experimenting with crisis-management roles within a structured educational setting. Such initiatives shift educators from the role of mere content transmitters to that of facilitators of simulated decision-making processes, in which students are asked to act as future professionals and, at the same time, as mediators of risk knowledge for communities and institutions.

At the university level, hazard-related XR environments link disciplinary teaching to emerging risk management roles. Sea-level-rise and flood-risk modules built on game engines and 3D GIS require geography, civil engineering, and environmental science students to interrogate model outputs, combine measures, and justify adaptation choices [99; 36; 25]. Real - world - based immersive VR for volcanology lets students and early-career researchers explore high-resolution outcrop models and landscapes, practising observation and communication in field - like settings without logistical constraints [98]. Flood-preparedness metaverse scenarios and serious games position university learners as crisis coordinators or community leaders who interpret alerts and coordinate basic actions, with outcomes measured through perceived usefulness, presence, and preparedness [123; 73; 121]. These deployments are embedded in courses and hackathons but rarely include practicing CI operators or emergency staff.

Finally, immersive technologies extend to university laboratories and research environments, where they support procedural training and safety management. In [75], VR inspections are used to train safety and health inspectors, laboratory staff, and students in hazard recognition, chemical safety, and compliance, minimizing the need to interrupt real experiments.

These examples show how immersive systems integrate training, assessment, and reflection, offering flexible solutions for both educational and professional contexts. When carefully designed, such environments enable students and teachers to connect technical instruction, behavioral training, and critical reflection within a single learning trajectory. In schools, serious games and VR applications for evacuation and fire management [84, 94, 102, 115] help pupils internalize rules and procedures, while at the same time strengthening the role of teachers as risk mediators and guides during emergencies. In university and professional settings, multi-device platforms and project-based formats such as *x3D training* [49] and *dual hackathons* [66] allow students to rehearse in advance the analytical, decision-making, and communication responsibilities that characterize future roles in safety and critical-infrastructure management. This line of research points to the emergence of a dual pedagogical function of immersive training: on the one hand as a medium for risk education (developing awareness and behavioral competence), and on the other as a professional training tool (developing the analytical, technical, and design thinking of future practitioners). Overall, these studies illustrate that, when immersive environments are grounded in solid educational design principles, they enhance not only cognitive learning but also motivation, reflection, and emotional engagement - key components for developing a lasting culture of safety among educators and students [97, 112, 113]. By linking experiential learning with reflective practice, these approaches transform education itself into a platform for resilience, embedding safety and preparedness within the continuum of lifelong learning.

4.5.5. Citizen and Communities

At the societal level, educational technologies extend beyond professional or educational boundaries to engage citizens and communities in risk awareness and participatory resilience. Simulations designed for public education, and civic - protection campaigns use VR as a communication and awareness tool, translating technical scenarios into accessible narratives that empower individuals to act safely during crises. Such applications emphasize collective learning and social cognition, enabling communities to understand their infrastructural environments, practice emergency behavior, and develop trust in institutional response systems. Within this perspective, citizen-facing applications also address everyday safety in mobility infrastructures: VR training on a railway level crossing [86] supports pedestrians (especially students) in practicing safe crossing behavior and evaluates the experience through the System Usability Scale and sense-of-presence measures. In this sense, VR contributes not only to skill training but to community-based resilience education, reinforcing the shared responsibility between institutions and the public.

Within the hazard-focused set, several serious games and simulations treat citizens and local communities as 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 [37, 41]. Landslide and flood risk simulators have participants adjust slope or defence parameters and justify their choices, allowing researchers to identify misconceptions and shifts in perceived effectiveness of measures [40, 69, 70]. These tools build 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 over structural and non - structural measures, revealing tensions between development, safety, and equity, and the role of trust, experience, and responsibility in shaping preferences [39, 124, 125]. School-centred initiatives connect simulation and drills: in a tsunami project, inundation modelling informs whole - school route revisions and discussions with authorities [72] and, to support scalable preparedness exercises, an urban-evacuation VR training system based on 360° panoramas [96] adopts a lightweight pipeline to represent multi-site escape routes, at the cost of more limited interaction with the virtual environment. While a dual hackathon on immersive simulation convenes student teams, civil protection organizations, and local stakeholders to co-design emergency-training concepts [66]. XR frameworks for flood action and urban risk propose multi-profile environments for user risk training in the urban built environment [56] where residents, volunteers, and responders access role – specific views, but reported pilots remain small and evidence on long-term effects on citizen – institution relations is limited [38, 39, 56, 66, 72, 124, 125].

In parallel, interactive simulations addressing human-induced hazards also contribute to public preparedness. The serious-game scenario of a terrorist attack in a train station [61] exemplifies how immersive design can engage citizens in understanding emergency dynamics and protective decision-making, complementing community-based approaches and extending resilience education to intentional crises.

Overall, the diversity of stakeholders identified in the literature confirms that education technologies have evolved into a meta-paradigm for training on critical infrastructures, uniting technical, cognitive, and social dimensions. Findings converge on three key directions.

- Vertical adaptability: immersive tools can be calibrated to different competence levels, aligning cognitive load with user expertise, from specialists to citizens.
- Horizontal collaboration: multi-role simulations foster cooperation across sectors and professions, reducing communication bottlenecks and improving integrated response capacities.
- Contextual transferability: pedagogical and technical principles validated in one domain (e.g. industry, healthcare, education) can be applied to others, promoting a form of resilience education that transcends sectoral boundaries.

The most innovative and transversal applications, such as [30], exemplify the growing potential of multi-user immersive environments where operators, managers, and responders interact simultaneously within shared virtual spaces. These collaborative systems strengthen situational awareness, coordination, and inter-professional understanding, paving the way for a new generation of evidence-based, human-centered, and inclusive training ecosystems for safety and emergency management.

4.6. Implementation phase

After identifying who learns within resilience - oriented systems, it becomes equally important to understand when and where learning takes place. This section therefore explores the implementation phase of educational technologies across the critical - infrastructure lifecycle, highlighting how different stages, from planning to crisis response, shape pedagogical priorities and technological configurations.

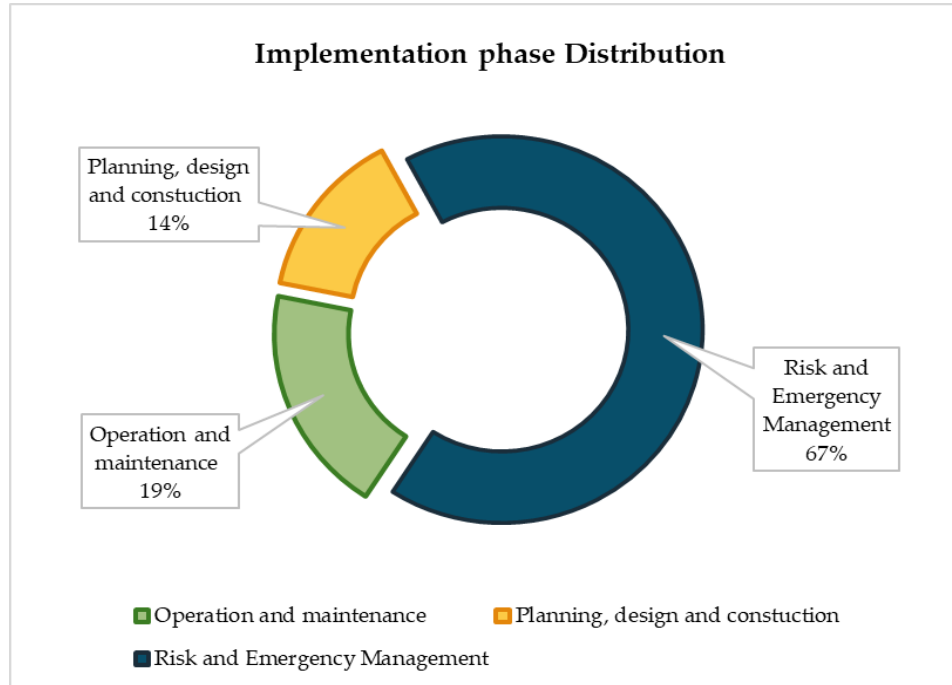


Figure 20: Implementation phase distribution. (Image created by the authors).

4.6.1. Planning, design and construction

During planning, design and construction, critical infrastructures exist primarily as systems in the making: construction sites, excavations, temporary works and workspaces that change over time, where geometric configuration, activity sequencing and the co-presence of equipment and people determine the risk profile. In this context, XR and BIM–VR environments do not merely represent the finished infrastructure; they are used to train workers and technicians on specific tasks before entering the site and to test alternative configurations of spaces, operational phases and procedures.

A first group of applications concerns geotechnical works and construction excavations, treated as temporary underground micro-infrastructure in which excavation volumes, access points and interactions with machinery define risk. In the immersive system for excavation safety [33], two real sites are modelled using terrains generated in Unity, reproducing the position, depth, width and texture of the excavations. In geotechnical drilling simulations [83], the focus shifts instead to the machine–environment relationship: the workspace is segmented into functional and risk zones (drilling area, control area, low-visibility zone, outer area), each associated with specific incident types and access rules. Taken together, these studies show how VR is used to make the “risk geography” of the construction site explicit and to let workers experience hazardous configurations and good practices before exposure in the real field.

A second line of work focuses on the construction of complex vertical infrastructures, in which the sequence of assembly phases is closely intertwined with the risk profile. The simulation proposed by Li et al. [50] breaks down the construction process of a wind tower into successive phases – foundation excavation and casting, reinforcement placement, transport and lifting of tower sections, assembly of nacelle, hub and blades – represented in an immersive VR environment. Throughout the sequence, participants are required to identify the hazards associated with the different construction phases, linking the reading of layout and operations to the systematic assessment of risks.

In continuity with these examples, road and metro work zones are repurposed for training as VR construction scenarios [47, 49, 51, 68], in which risk configurations observed in the field feed exercises in hazard recognition, selection of control measures and discussion of layout variants before their implementation on site.

On the methodological side, comparative studies on the instructional design of VR-based safety training [32] also show that, at this stage, it is not only the realism of the environment that matters, but also the way in which tasks, feedback and errors are orchestrated along the learning sequence, differently influencing the acquisition of declarative knowledge and the willingness to transfer it into practice.

Ultimately, these contributions suggest that the planning, design and especially construction phase constitutes a privileged field for the use of immersive technologies, in which sites, excavations and assemblies are conceived as controlled-risk laboratories. In these laboratories, immersive models both allow safety management practices to be tested and refined and support the creation of initial digital-twin nuclei that can be extended and reused in subsequent operation and maintenance phases.

4.6.2. Operation and maintenance

Operation and maintenance (O&M) are the longest and most knowledge-intensive phases of the infrastructure lifecycle. In these phases, digital and immersive technologies are increasingly used to sustain safety, efficiency, and decision support during routine as well as abnormal conditions. In these stages, training focuses on continuous monitoring, inspection, preventive actions, and the management of anomalies under operational constraints. XR, VR, and digital-twin environments can be understood as controlled, repeatable training and validation platforms where operators rehearse procedures, visualize system status, and anticipate failures without interrupting real operations [26, 59, 104, 106, 114, 118, 120].

Across the reviewed corpus, sector-specific applications show how immersive systems operationalize procedural knowledge and interface literacy. Applications are used to train routine operation, monitoring, and analysis around protective systems. VR tutorials for mobile flood protection units guide trainees through the full assembly sequence of demountable barriers, providing repetition and feedback on time and errors that mirrors real deployment tasks along rivers or dikes [101]. Flood-oriented digital twins and XR dashboards train users to operate observation and decision interfaces: loading scenarios, adjusting sea-level or rainfall inputs, reading water-level and inundation outputs, and checking the status of defenses in 3D GIS scenes [99, 36, 25]. Volcanology field and unrest exercises use VR for analytical work, having students and junior experts inspect virtual outcrops, interpret monitoring time series, and propose alert levels with probabilistic tools, echoing steps in operational surveillance [98, 71].

Comparable solutions emerge in 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 [31, 104, 109, 117, 120]. Operators practice isolation, lock-out/tag-out (LOTO) procedures, circuit testing, and emergency shutdowns under controlled conditions, while data-driven modules record actions and errors for feedback and assessment and, where applicable, certification. Across sectors such as open-cast mining, maritime transport, offshore power systems, chemical laboratories, and aviation, VR and AR-based safety courses similarly guide workers through inspection routines, standardized safety checks, and emergency responses, improving hazard recognition, engagement, and adherence to procedures [26, 27, 29, 59, 89, 104, 105, 106, 109, 114, 118]. Within chemical-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 [75]. Beyond scenario fidelity, controlled comparisons of instructional designs within VR indicate that pedagogically grounded approaches can materially affect learning outcomes: productive-failure-based VR training has been shown to outperform directive-instruction designs in declarative safety knowledge acquisition and retention for confined-space preparation tasks [32]. Evidence syntheses on VR/AR-based safety training underline that these approaches are particularly effective for procedural learning and risk awareness, while calling for more standardized evaluation frameworks and stable integration into organizational training programmes [29, 60]. In transport systems, VR training for locomotive crews enables operators to practice diagnostic procedures and emergency management within interactive digital-twin environments [35]. Fire-related XR systems such as *GUIDE2FR* [65] and tunnel-maintenance simulators [28, 58] link routine inspection with

emergency preparedness, allowing users to monitor sensors, verify alarms, and switch between normal and alert modes within the same digital twin. Taken together, these examples illustrate a functional convergence between maintenance training and safety rehearsal: the same virtual infrastructure supports both preventive management and rapid response.

More advanced approaches incorporate real-time data streams into training environments, moving toward cyber-physical continuity. Oil-depot and hydropower-plant digital twins [30, 64] synchronize IoT sensors, alarms, and control parameters with interactive 3D models, and learning-factory implementations couple digital twins of robot cells and production lines with VR-based operator training [105], providing operators with immediate feedback on equipment status and supporting predictive maintenance strategies. In such contexts, immersive interfaces enable multi-scale understanding, from component to system level, bridging the cognitive gap between monitoring dashboards and physical assets.

Overall, these applications indicate that maintenance and operational training are converging toward integrated, data-informed ecosystems, where continuous learning supports both reliability and emergency readiness. This convergence marks the transition from static maintenance routines to more dynamic resilience management, bridging everyday operations and crisis response.

4.6.3. Risk and Emergency Management

Many applications use XR and serious games to rehearse how people manage risk before and during emergencies [146, 147, 148, 149]. 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 [65]. Complementarily, some studies operate at a planning scale and compare alternative disaster-preparedness strategies in terms of expected effectiveness and health-related impacts [46], while others embed intelligence directly into wayfinding by contrasting dynamic and static guidance to optimize evacuation time and safety [23]. Related VR preparedness frameworks 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 [121].

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 [37, 41, 73]. 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 [40, 69, 70]. 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 [72, 100].

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 [18, 53, 91, 97, 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 [93, 77, 126]. Some drills also couple evacuation with immediate mitigation actions, such as isolating the hazard source as part of the response sequence [103]. Within this stream, drills for occupants and students alternate operational tasks (detecting the fire, selecting escape routes, using extinguishers, and managing distance and time) [115] with more procedural and organizational sequences (roles, evacuation order, collective protocols, and meeting points) [84, 94]. Evaluation encompasses both awareness/competence indicators and scenario performance [102, 116, 48], as well as comparisons across training modalities (e.g., AR versus video) in terms of retention, motivation, and self-efficacy [76], with variants deployed in existing buildings and, in some cases, extended to support search-and-rescue tasks [21, 87, 20]. 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 [119] to naval fire drills up to the muster area [126], and simulators that also support fire-brigade organization and commanding decision-making [110]. 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 [90].

Similar behavioral frameworks have also been applied to human-induced crises, such as the simulation of a terrorist attack [61], 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 [86].

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 [36, 78, 79, 81, 99]. 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 [56] to place-based tsunami drills that train signage interpretation and route choice before real events [96]. In parallel, collaborative multi-hazard environments extend preparedness to intentional crises and support what-if exploration and decision strategies in complex city scenarios [47], while civil-protection initiatives combine emergency simulation and hackathons to develop solutions for communication, coordination, and response support [66]. 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 [36, 39, 123, 124, 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 [28, 38, 66, 77, 96].

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 [57, 58]. 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 [28]. 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 [24]. 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 [34]. Related patterns recur in firefighter training on real buildings for preparedness and intervention [82], complex scenarios that require multi-agency coordination and rapid decision-making [85], industrial contexts such as oil depots that combine preventive inspection with multi-role drills and penalties for errors and delays [30], and systems that introduce automation/robotics to guide action and support personnel assessment [22], as well as low-frequency/high-risk events in constrained environments such as mines [93].

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 [56, 74, 121]. 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 [92].

5. Discussion

Across the reviewed corpus, the convergence of educational, technological, and infrastructural dimensions reveals a profound transformation in how resilience and risk management are conceived within the field of critical infrastructures. What emerges is a shift from isolated training applications toward integrated learning ecosystems where simulation, data, and human interaction coalesce into dynamic environments for experiential and adaptive learning. These ecosystems blur the boundaries between education, operation, and governance, making training an ongoing process rather than a discrete activity. Immersive environments—whether VR, AR, or hybrid XR configurations—function not merely as didactic tools but as cognitive infrastructures that reproduce the systemic complexity, temporal dynamics, and interdependencies of real operations. Within this paradigm, learning occurs through enactment and reflection: users do not only practice procedures but experience the constraints, coordination logics, and emotional conditions of real emergencies. In this sense, the pedagogical value of simulation lies less in its realism per se than in its ability to embed learners within the logic of systemic interdependence that defines critical infrastructures.

The synthesis across technological layers shows a clear evolution from static, rule-based simulations toward adaptive, data-driven, and multi-user architectures that approach the logic of cyber-physical systems. Rule- and knowledge-based engines remain valuable where procedural consistency and formal verification are essential, yet they are increasingly complemented by agent-based, AI-enhanced, and digital-twin frameworks capable of reproducing feedback loops between environment and behavior. This progression mirrors the digital transformation of the infrastructures themselves: as assets become sensorized and interconnected, their virtual counterparts evolve from training simulators into living laboratories for operational learning. On the interaction side, the continuum extends from non-immersive desktop interfaces to fully embodied and collaborative metaverse systems, each level calibrated to a specific balance of accessibility, realism, and coordination. While visual immersion enhances presence and engagement, cognitive immersion—the capacity to reason, decide, and collaborate under uncertainty—emerges as the real driver of learning transfer. In this respect, multi-user and metaverse environments mark a decisive turning point, enabling collective rehearsal, inter-agency coordination, and distributed situational awareness across domains once trained separately.

At the same time, significant limitations persist that prevent the full realization of this vision. Cultural and institutional barriers remain among the most critical: immersive technologies are often perceived as experimental or peripheral, and their integration into formal curricula or regulatory frameworks is still fragmentary. Experienced professionals may show skepticism toward game-like interfaces, while academic institutions and public agencies struggle to maintain continuity between pilot projects and operational adoption. Methodological limitations further constrain progress. Evaluation is predominantly focused on usability and short-term engagement, rarely extending to behavioral validation, longitudinal retention, or transferability to real-world performance. Metrics capable of quantifying resilience-related learning outcomes—such as situational awareness, decision accuracy, or adaptive collaboration—are still embryonic. Technological constraints also play a role: interoperability between XR platforms, BIM or GIS datasets, and real-time sensor streams remains inconsistent, and the rapid obsolescence of hardware and software threatens the sustainability and reproducibility of training assets. A neglected yet crucial issue concerns the preservation of digital learning experiences: 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 once technologies or operating systems evolve. In this sense, the fragility of digital products mirrors the fragility of the infrastructures they aim to protect, underscoring the need for robust strategies of conservation, metadata standardization, and open access to simulation datasets.

Looking ahead, the future of resilience education will depend on the capacity to integrate technological sophistication with human-centered design and evaluative rigor. Three strategic directions emerge. First, there is a need to establish shared assessment frameworks that go beyond usability and motivation, linking learning analytics with performance indicators that reflect real operational competence. Second, adaptive intelligence—enabled by AI and data analytics—should be leveraged not only for scenario realism but for personalized learning trajectories that accompany operators throughout their careers, connecting training data to actual performance metrics within digital-twin environments. Third, sustainability must become a

design principle: immersive products should be conceived as part of living repositories of collective knowledge, interoperable across institutions, hazards, and technologies. The challenge is therefore dual: technological, in maintaining the longevity and adaptability of virtual systems, and cultural, in fostering interdisciplinary literacy and openness to continuous learning.

In sum, the reviewed literature confirms that immersive and data-driven education has the potential to redefine how societies prepare for, respond to, and learn from crises affecting critical infrastructures. Yet its consolidation as an evidence-based practice will depend on long-term commitment to evaluation, preservation, and inclusivity. The transition from experimental simulation to institutional learning infrastructure requires bridging the gap between innovation and governance, ensuring that every digital experience produced today contributes to the cumulative intelligence of tomorrow's resilient operators.

6. Conclusions

Digital transformation, increased systemic risks and the growing complexity of critical infrastructure require a redefinition of the role of professionals engaged in asset management. In this context, the figure of the Resilient Operator [13,14,15] emerges: a worker who is not only capable of managing assets and processes, but also of adapting, learning, and reacting effectively to new challenges and work ecosystems. This concept resonates strongly with recent discussions on Construction 5.0 and Operator 5.0, where the evolution of industrial paradigms emphasizes human - centricity, sustainability, and resilience. The Resilient Operator can thus be interpreted as the critical infrastructure counterpart of Operator 5.0, embodying the fusion between human expertise and machine efficiency. In this vision, operators are no longer passive executors but active co - creators of resilient systems, able to collaborate with advanced technologies - digital twins, AI, IoT, and automation - while preserving the centrality of human judgment and adaptability. Recent literature also highlights that the COVID - 19 pandemic exposed the fragility of existing manufacturing and infrastructure systems, underscoring the workforce as both the most agile and most vulnerable resource. Making human operators more resilient - through training, education, and systemic support - becomes the cornerstone of building organizations capable of withstanding disruptions. The Resilient Operator 5.0 paradigm, developed in the context of Industry 5.0, demonstrates how resilience must be framed not only at the technological or systemic level, but also at the human one, strengthening cognitive, emotional, and collaborative dimensions alongside technical expertise. Within the critical infrastructure domain, the Resilient Operator thus emerges as a new professional paradigm, bridging tradition and innovation, and combining established technical skills with the flexibility, agility, and cross - domain awareness required by today's contexts. Their training and development represent the most advanced outcome of reskilling and upskilling programmes supported by Education Technology.

7. 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
IoT	Internet of Things
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
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 "augmented reality" OR "mixed reality" OR "extended 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 (EXCLUDE(SUBJAREA,"MEDI") OR EXCLUDE(SUBJAREA,"IMMU") OR EXCLUDE(SUBJAREA,"VETE") OR EXCLUDE(SUBJAREA,"DENT") OR EXCLUDE(SUBJAREA,"PHAR") OR EXCLUDE(SUBJAREA,"NEUR") OR EXCLUDE(SUBJAREA,"NURS"))

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Annex 2



GLOSSARIO



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3D MODEL

IT Un modello 3D (modello tridimensionale) è una rappresentazione matematica di un oggetto tridimensionale. È un elemento chiave della computer grafica 3D, del disegno industriale, della progettazione architettonica e della stampa tridimensionale. Il processo che riguarda la creazione di un modello 3D, è detto modellazione 3D (modellazione tridimensionale), è il processo atto a definire una forma tridimensionale in uno spazio virtuale generata su computer. Che si distingue da altri tipi di modellazione tridimensionale, come ad esempio la scultura tradizionale.

EN A 3D model (three-dimensional model) is a mathematical representation of a three-dimensional object. It is a key element of 3D computer graphics, industrial design, architectural design and three-dimensional printing. The process of creating a 3D model is called 3D modeling (three-dimensional modeling), it is the process of defining a three-dimensional shape in a virtual space generated on a computer. Which is distinct from other types of three-dimensional modeling, such as traditional sculpture.

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ARTIFICIAL INTELLIGENCE

IT Il termine Intelligenza Artificiale (IA) è stato coniato più di 50 anni fa e viene usato per indicare sistemi in grado di simulare l'intelligenza umana e risolvere problemi tipicamente riservati all'uomo. Più che di una vera e propria intelligenza la IA è un sistema razionale, che cerca risposte a quesiti specifici sfruttando processi di addestramento in grado di auto migliorarsi.

EN The term Artificial Intelligence (AI) was coined more than 50 years ago and is used to refer to systems capable of simulating human intelligence and solving problems typically reserved for humans. Rather than true intelligence, AI is a rational system that seeks answers to specific questions by leveraging training processes that can improve themselves over time.

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AUGMENTED REALITY

- IT** L'Augmented Reality (AR) è una tecnologia che combina oggetti virtuali 3D con il mondo reale in tempo reale. Questo è possibile grazie all'aggiunta di contenuti generati dal computer, come immagini, suoni o dati, a ciò che vediamo. Migliora il modo in cui percepiamo e interagiamo con l'ambiente circostante. Nel corso degli anni, la realtà aumentata è avanzata considerevolmente e oggi viene utilizzata in molti settori, come l'educazione, l'intrattenimento e diverse industrie.
- EN** Augmented Reality (AR) is a technology that combines 3D virtual objects with the real world in real time. This is possible by adding computer generated content like images, sounds, or data to what we see. It improves how we perceive and interact with our surroundings. Over the years, augmented reality has advanced considerably and it is now being used in many areas, such as education, entertainment and across different industries.

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AVATAR

- IT** L'Avatar è una rappresentazione virtuale 2D o 3D personalizzata di un'identità fisica in un ambiente digitale, la sincerità della figura non costituisce un obbligo. Può rappresentare una persona reale o un'intelligenza artificiale, come personaggi non giocanti o assistenti virtuali, e svolge un ruolo cruciale nel riconoscimento e nell'interazione tra utenti. Gli avatar trovano applicazione in vari contesti, dai videogiochi ai mondi virtuali non ludici, social network e ambienti di lavoro digitali.
- EN** An Avatar is a personalized 2D or 3D virtual representation of a physical identity in a digital environment; the figure's sincerity is not a requirement. It can represent a real person or an artificial intelligence, such as NPCs (Not Playable Character) or virtual assistants, and plays a crucial role in user recognition and interaction. Avatars find application in a variety of contexts, from video games to non-gaming virtual worlds, social networks, and digital work environments.

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BIM

IT Il BIM (Building Information Modeling) è un insieme di metodologie basate su processi digitali per la creazione e la gestione di dati su edifici e infrastrutture, durante il loro intero ciclo di vita, che consente una collaborazione multidisciplinare tramite un modello 3D condiviso. Integrando informazioni geometriche e semantiche, il modello stesso diventa un database di tutti i dati rilevanti di un progetto, supportando un migliore processo decisionale, efficienza dei costi e gestione dei rischi, dalla progettazione preliminare alla dismissione.

EN BIM (Building Information Modeling) is a set of methodologies based on digital processes for creating and managing data about buildings and infrastructure, throughout their entire lifecycle, enabling multi-disciplinary collaboration via a shared 3D model. By integrating geometrical and semantic information, the model itself becomes a database of all the relevant data of a project, supporting better decision-making, cost efficiency, and risk management, from initial design to decommissioning.

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DIGITAL TWIN

IT Una rappresentazione virtuale dinamica e ad alta fedeltà di oggetti fisici, sistemi o processi, aggiornata in tempo reale con dati raccolti da AI, IoT, sensori e tecnologie avanzate. Consente simulazioni, monitoraggio e ottimizzazione, migliorando efficienza, sostenibilità e sicurezza. Nell'Industria 5.0 evolve in Human Digital Twin (HDT), integrando benessere umano, emozioni e strumenti come BIMtoBEM, XR e blockchain per una produzione resiliente e umanocentrica.

EN A dynamic and high-fidelity virtual representation of physical objects, systems, or processes, updated in real-time with data from AI, IoT, sensors, and advanced technologies. It enables simulations, monitoring, and optimization, improving efficiency, sustainability, and safety. In Industry 5.0, it evolves into the Human Digital Twin (HDT), integrating human well-being, emotions, and tools like BIMtoBEM, XR, and blockchain for resilient, human-centered production.

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E LEARNING

IT L'eLearning si riferisce all'uso di tecnologie elettroniche per accedere a contenuti educativi al di fuori di un'aula tradizionale. Comprende una varietà di formati, tra cui corsi online, classi virtuali e strumenti di collaborazione digitale, permettendo agli studenti di apprendere da remoto e con i propri ritmi. Questo approccio sfrutta risorse multimediali, valutazioni interattive e piattaforme di comunicazione per facilitare l'apprendimento. L'eLearning è diventato una strategia chiave nell'istruzione superiore per migliorare i risultati educativi e stimolare la motivazione degli studenti.

EN eLearning refers to the use of electronic technologies to access educational curriculum outside of a traditional classroom. It encompasses a variety of formats, including online courses, virtual classrooms, and digital collaboration tools, enabling learners to study remotely and at their own pace. This approach leverages multimedia resources, interactive assessments, and communication platforms to facilitate learning. eLearning has become a key strategy in higher education to enhance educational outcomes and stimulate student motivation.

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ENGAGEMENT

IT L'engagement nella realtà virtuale (VR) è il livello di coinvolgimento emotivo, cognitivo e fisico dell'utente durante l'interazione con ambienti virtuali. Questo concetto è fondamentale per valutare l'efficacia delle esperienze VR: un alto engagement può ridurre lo stress e migliorare l'apprendimento. Realismo, interattività, immersione e coinvolgimento emotivo giocano un ruolo chiave nel rendere le esperienze VR funzionali e memorabili, soprattutto quando progettate per suscitare emozioni e favorire l'interazione attiva.

EN Engagement in virtual reality (VR) is the level of emotional, cognitive, and physical involvement of the user during interaction with virtual environments. This concept is crucial for assessing the effectiveness of VR experiences: high engagement can reduce stress and improve learning. Realism, interactivity, immersion, and emotional involvement play a key role in making VR experiences functional and memorable, especially when designed to evoke emotions and encourage active interaction.

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EXPERIENTIAL LEARNING

IT L'apprendimento esperienziale è un processo educativo che si basa sull'esperienza diretta, coinvolgendo aspetti cognitivi, emotivi e sensoriali. In questo modello pedagogico, lo studente contribuisce attivamente alla costruzione della conoscenza attraverso l'interazione, la riflessione e l'applicazione pratica. Questo approccio sviluppa capacità di problem-solving, stimola la creatività e accresce l'autoconsapevolezza, migliorando atteggiamenti e comportamenti grazie all'auto-osservazione e all'osservazione esterna.

EN Experiential learning is an educational process based on direct experience, involving cognitive, emotional, and sensory aspects. In this pedagogical model, the student actively contributes to the construction of knowledge through interaction, reflection, and practical application. This approach develops problem-solving skills, stimulates creativity, and enhances self-awareness, improving attitudes and behaviors through self-observation and external observation.

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EXTENDED REALITY

IT Termine emergente che include in maniera generica tutte le tecnologie immersive in grado di generare o modificare la realtà ampliando i confini della percezione umana. Tra queste si annoverano la Realtà Virtuale (VR), la Realtà Aumentata (AR) e la Realtà Mista (MR). Secondo alcuni esperti del settore, il termine "estesa", per definizione, escluderebbe la VR, poiché in quest'ultima la realtà non viene estesa, bensì sostituita. Per questa ragione, xReality (XR) potrebbe essere ritenuto un termine più appropriato, dove "x" funge da segnaposto per qualsiasi forma di nuova realtà.

EN An emerging umbrella term that encompasses all immersive technologies capable to generate or modify reality expanding the limits of human perception. These include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). According to some industry experts, the term "extended" would, per definition, exclude VR, as in VR, reality is not extended but rather replaced. For this reason, xReality (XR) could be considered more appropriate term, where "x" serves as a placeholder for any form of new reality.

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GAMIFICATION

IT La gamification è l'applicazione di elementi e dinamiche tipiche del gioco in contesti non ludici, come l'edilizia e le infrastrutture, per aumentare il coinvolgimento e la motivazione degli utenti. Integrando la gamification con tecnologie come il Building Information Modeling (BIM), la realtà virtuale (VR) e la realtà aumentata (AR), è possibile migliorare la formazione degli utenti in progetti complessi simulando molteplici scenari in modo immersivo. La VR e l'AR consentono agli utenti di interagire con modelli digitali in ambienti realistici, rendendo più intuitivo il processo decisionale e l'addestramento. Ad esempio, si possono creare simulazioni per la formazione sulla sicurezza o per ottimizzare il flusso di lavoro in cantiere.

EN Gamification is the application of typical game elements and dynamics in non-gaming contexts, such as construction and infrastructure, to increase user engagement and motivation. By integrating gamification with technologies like Building Information Modeling (BIM), Virtual Reality (VR), and Augmented Reality (AR), it is possible to enhance user training in complex projects by simulating multiple scenarios in an immersive way. VR and AR allow users to interact with digital models in realistic environments, making decision-making and training more intuitive. For example, simulations can be created for safety training or to optimize workflow on construction sites.

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HEAD - MOUNTED DISPLAYS

IT Un HMD è un dispositivo indossabile sulla testa, generalmente un casco o degli occhiali, che, con l'ausilio di un sistema di tracciamento, consente a un utente la percezione senza soluzione di continuità di un ambiente virtuale in un campo visivo variabile che va da 110° a 130°. Questi dispositivi sono dotati di due schermi, uno per ciascun occhio, che presentano due immagini differenti renderizzate in base alla visione di ogni occhio. Questo fornisce segnali di profondità binoculare realistici.

EN An HMD is a head-mounted device, usually a helmet or goggles, that uses a tracking system to provide the user with seamless perception of a virtual environment in a variable field of view ranging from 110° to 130°. These devices are equipped with two screens, one for each eye, which present two different images, rendered according to the vision of each eye. This provides realistic binocular depth signals.

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IFC

IT Schema di dati standardizzato aperto (ISO 16739-1:2024) sviluppato da buildingSmart per promuovere la metodologia openBIM e migliorare lo scambio e la condivisione di dati provenienti da modelli parametrici. Codifica l'identità, le caratteristiche e le relazioni di oggetti, concetti astratti (es: performance e costing), processi e persone nel settore delle costruzioni e del Facility Management, migliorando l'interoperabilità tra diversi software BIM.

EN The standardized open data schema (ISO 16739-1:2024) developed by buildingSmart aims to promote the openBIM methodology and improve the exchange and sharing of data from parametric models. It encodes the identity, characteristics, and relationships of objects, abstract concepts (e.g., performance and costing), processes, and people in the construction and Facility Management sectors, enhancing interoperability between different BIM software.

References:

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IMMERSIVE VIRTUAL ENVIRONMENT

IT Un ambiente virtuale immersivo (AVI) è uno spazio simulato creato da tecnologie come VR, AR e MR, che offre esperienze interattive e coinvolgenti. Grazie a visori, cuffie e interfacce tattili, l'utente esplora scenari tridimensionali, stimolando vista, udito e tatto. Le caratteristiche principali includono immersione sensoriale, interattività, personalizzazione, sicurezza e feedback immediato, supportando un apprendimento esperienziale sicuro e competenze come pensiero critico e comunicazione.

EN An immersive virtual environment (IVE) is a simulated space created using technologies such as VR, AR, and MR, designed to offer interactive and engaging experiences. Using headsets, spatial audio, and haptic interfaces, users explore 3D scenarios, stimulating sight, hearing, and touch. Key features include sensory immersion, interactivity, personalization, safety, and immediate feedback, supporting safe experiential learning and skills such as critical thinking and communication.

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METaverse

IT Il metaverso è un ecosistema digitale interoperabile di ambienti 3D immersivi, accessibili in tempo reale da una molteplicità di dispositivi. Gli utenti interagiscono tramite identità digitali dette avatar, con esperienze sincrone e persistenti anche in loro assenza. Eventi, oggetti e identità digitali si mantengono nel tempo. Favorisce interazioni sociali, economiche e culturali. Si basa su tecnologie abilitanti della X-Reality come realtà virtuale, aumentata e mista.

EN The metaverse is an interoperable digital ecosystem of immersive 3D environments, accessible in real time from multiple devices. Users interact through digital identities called avatars, enjoying synchronous and persistent experiences even when they are offline. Events, objects, and digital identities endure over time. It fosters social, economic, and cultural interactions. It relies on X-Reality enabling technologies such as virtual, augmented, and mixed reality.

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MIXED REALITY

IT Concetto in continua evoluzione, privo di una definizione universalmente concordata, evoca ambienti di diversa natura in cui oggetti reali e virtuali, e i loro dati, coesistono e interagiscono in tempo reale all'interno di un'unica interfaccia. Introdotta per la prima volta nel contesto del Vitruality Continuum (VC) per indicare tutte le sfumature presenti tra un ambiente completamente reale ed una totalmente virtuale. In funzione della quantità di oggetti reali e virtuali nell'ambiente, si distinguono stadi intermedi come la Realtà Aumentata (AR) e la Virtualità Aumentata (AV). Studi recenti propongono l'AR-Continuum basato sul grado di "presenza locale": maggiore è l'integrazione percepita dall'utente del contenuto virtuale all'interno dell'ambiente ibrido, più ci si avvicina alla Realtà Mista; al contrario, quando il contenuto è una semplice sovrapposizione si parla di Realtà Assistita.

EN An evolving concept, it evokes a variety of environments in which real and virtual objects, and their data, coexist and interact in real time within a single interface. The term was first introduced in the context of the Vitruality Continuum (VC) to indicate all the nuances present between a fully real and a fully virtual environment. Depending on the amount of real and virtual objects in the environment, intermediate stages such as Augmented Reality (AR) and Augmented Virtuality (AV) are distinguished. Recent studies propose an AR-Continuum based on the degree of 'local presence': the greater the perceived integration of the virtual content in the physical environment, the closer one gets to Mixed Reality; on the contrary, when the content is merely superimposed, one speaks of Assisted Reality.

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MOTION SICKNESS

IT La chinetosi, o motion sickness, è una condizione caratterizzata da una sensazione di malessere provocata dal movimento, reale o virtuale, che si verifica spesso durante viaggi o immersioni in realtà virtuale. I sintomi includono nausea, vomito, pallore, sudorazione, ipersalivazione e la cosiddetta sindrome di sopite (sonnolenza e affaticamento). Le cause precise e i meccanismi neurobiologici restano incerti, ma l'ipotesi del conflitto sensoriale è la più accreditata. La suscettibilità varia tra individui, influenzata da fattori genetici, ambientali e dalla privazione del sonno.

EN Motion sickness is a condition characterized by a feeling of discomfort caused by real or virtual motion, often occurring during travel or virtual reality immersion. Symptoms include nausea, vomiting, pallor, sweating, hypersalivation and the so-called sopite syndrome (drowsiness and fatigue). The accurate causes and neurobiological mechanisms remain uncertain, but the sensory conflict hypothesis is the most widely accepted. Susceptibility varies among individuals, influenced by genetic, environmental factors, and sleep deprivation.

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OPENBIM

IT OpenBIM è un processo collaborativo e neutrale che estende i benefici del BIM. La differenza principale tra queste due metodologie risiede nell'interoperabilità: mentre il BIM spesso impiega formati proprietari "chiusi" che possono limitare la compatibilità tra software, openBIM adotta standard "aperti", come IFC, potenziando la condivisione dei dati tra diversi software e stakeholder e migliorando l'efficienza dei progetti e degli asset durante tutto il loro ciclo di vita.

EN OpenBIM is a collaborative and neutral process that extends the benefits of BIM. The main difference between these two methodologies lies in interoperability: while BIM often uses proprietary "closed" formats that can limit compatibility between software, openBIM adopts "open" standards, such as IFC, enhancing data sharing among different software and stakeholders, and improving the efficiency of projects and assets throughout their lifecycle.

References:

- <https://www.buildingsmart.org/>

VIRTUAL REALITY

IT La Realtà Virtuale (VR) è una tecnologia che simula uno spazio tridimensionale immersivo creato digitalmente, che può essere simile o completamente diverso dal mondo reale. L'utente può muoversi nell'ambiente virtuale, esplorarlo da diversi punti di vista e interagire con esso per mezzo di interfacce non convenzionali, quali occhiali e caschi su cui viene rappresentata la scena ed eventuali dispositivi per la riproduzione di suoni, la simulazione di stimoli tattili e la traduzione di movimenti reali in istruzioni per il software.

EN Virtual Reality (VR) is a technology that simulates a digitally created immersive three-dimensional space that can be similar to or completely different from the real world. The user can move through the virtual environment, explore it from different angles and interact with it by means of unconventional interfaces, such as goggles and helmets on which the scene is represented and possible devices for reproducing sounds, simulating tactile stimuli and translating real movements into instructions for software.

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VR PERIPHERALS

IT Le periferiche VR sono dispositivi hardware progettati per offrire un'esperienza immersiva in realtà virtuale, consentono all'utente di interagire con l'ambiente virtuale e di percepire sensazioni che si avvicinano molto alla realtà. Comprendono: dispositivi di visualizzazione (come i visori VR), dispositivi di input (quali controller e guanti aptici), sistemi di feedback sensoriale (come tute aptiche e pedane), e dispositivi di tracking (sensori e telecamere).

EN VR peripherals are hardware devices designed to provide an immersive virtual reality experience; they allow the user to interact with the virtual environment and perceive sensations that closely approximate reality. They include: display devices (such as VR viewers), input devices (such as controllers and haptic gloves), sensory feedback systems (such as haptic suits and footpads), and tracking devices (sensors and cameras).

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