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Game-based learning for critical infrastructure training: Designing serious games for decision-making skills

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Abstract

Critical infrastructures operate in highly complex, interconnected, and risk-prone environments that require effective decision-making under uncertainty, time pressure, and incomplete information. Traditional training approaches often fail to capture the dynamic conditions of real-world infrastructure disruptions. In this context, Game-Based Learning (GBL) and serious games offer useful approaches for developing decision-making skills in high-risk domains. This paper explores the role of serious games in critical infrastructure training and proposes a design framework for developing game-based environments that support situational awareness, risk assessment, and collaborative decision-making. Drawing on recent literature, the study identifies key design principles such as scenario realism, adaptive feedback, and system responsiveness. The findings suggest that serious games can improve the preparedness of professionals and support more effective responses in complex and high-risk environments.

Keywords: Immersive serious games; Adult education; Virtual reality; Decision-making; Critical situations; Experiential learning; Game-based learning

1. Introduction

Critical infrastructures (CIs) are fundamental systems of modern societies and include sectors such as energy, transportation, healthcare, water systems, and digital communications (Council of the European Union, 2008). The increasing use of digital technologies and the growing interconnection between systems have improved their efficiency, but at the same time have made them more exposed to threats such as cyberattacks, natural disasters, and cascading failures (Linkov et al., 2018; Kröger, 2019; Dunn Cavelty, 2020; Rinaldi et al., 2001). Managing these infrastructures involves decision-making in situations where uncertainty, time pressure, and incomplete information are often present, and where the consequences can be severe (Pescaroli& Alexander, 2018; Ouyang, 2014; Zio, 2016). However, traditional training approaches, such as lectures and static simulations, do not always prepare professionals adequately for these conditions (Salas et al., 2012; Lateef, 2010).

In this light, Game-Based Learning (GBL) has gained attention as an approach that combines interactive technologies with experiential learning. More specifically, serious games allow learners to engage with realistic scenarios, try different strategies, and receive immediate feedback on their decisions (Plass et al., 2015; Boyle et al., 2016; Connolly et al., 2012). Serious games have also been widely recognized as powerful educational and training tools in the broader literature (Zyda, 2015; Squire, 2015; Alvarez & Djaouti, 2017). Research suggests that serious games can support skills such as problem-solving, systems thinking, and adaptive decision-making (Wouters et al., 2013; Hamari et al., 2016). They also provide a safe environment where high-risk situations can be explored without real-world consequences (Gee, 2007; Graafland et al., 2012), which makes them particularly suitable for CI training. Despite these advantages, there is

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still limited research on how serious games should be designed specifically for decision-making training in CI contexts. This paper proposes a framework for serious game development aimed at supporting decision-making in complex and high-risk environments.

2. Research Questions and Methodology

2.1. Research Questions

This study is guided by the following research questions:

- RQ1: How can Game-Based Learning enhance decision-making skills in CI contexts?
- RQ2: What design elements are essential for serious games targeting high-risk environments?
- RQ3: How can serious games support situational awareness, risk assessment, and collaborative decision-making?
- RQ4: What is the role of artificial intelligence in optimizing serious game–based training systems?

2.2. Methodology

This study adopts a qualitative research approach based on a structured literature review of recent studies (2015–2025) in the fields of Game-Based Learning, serious games, decision-making, and CI training. Recent research has also highlighted the role of mobile technologies, ICT tools, and AI-based applications in supporting learning and assessment processes in both general and special education contexts (Politi-Georgousi&Drigas, 2020; Drigas& Theodorou, 2016; Chaidi et al., 2021).

The methodology includes:

- Analysis of peer-reviewed journal articles and conference papers
- Comparative evaluation of existing serious game frameworks
- Synthesis of interdisciplinary findings from education, cognitive science, and systems engineering

The study follows an interpretive and analytical approach, aiming to identify patterns, design principles, and emerging trends in the development of serious games for high-risk environments (Susi et al., 2007; Arnab et al., 2015).

3. Theoretical Foundations of Game-Based Learning and Decision-Making

3.1. Game-Based Learning and the Experiential Learning

GBL is grounded in constructivist and experiential learning theories that emphasize the importance of active learner involvement, knowledge construction through experience, and learning by doing (Plass et al., 2015; Piaget, 1952; Vygotsky, 1978). Experiential learning theory posits that knowledge is created through the transformation of experience by way of iterative cycles of action, reflection, conceptualization, and experimentation (Kolb, 1984). GBL, when embedded in serious games, operationalizes these theoretical principles by immersing learners in dynamic environments where they interact with complex systems and receive direct feedback on their decisions (Plass et al., 2015; Boyle et al., 2016).

Unlike traditional pedagogical methods that rely predominantly on knowledge transmission and tend to foster learner passivity, GBL actively engages a range of cognitive processes including perception, problem-solving, and decision-making (Wouters et al., 2013). Moreover, recent research highlights that digital and AI-enhanced learning environments can significantly improve higher-order cognitive skills, collaborative learning, and instructional innovation in contemporary education (Simos et al., 2026; Simos &Katsiampoura, 2025; Simos, 2025a). In addition, emerging research in educational robotics, mobile learning, and AI-enhanced environments has shown that digital tools can meaningfully improve problem-solving, creativity, and higher-order thinking skills (Moraiti et al., 2022; Pergantis&Drigas, 2024; Pergantis et al., 2025).

Due to the motivating effect of real-life interaction, serious games can serve as effective means to raise motivation levels, while a task-oriented approach to learning with clear objectives, challenges, and rewards is being pursued (Hamari et al., 2016). This aligns with self-determination theory, which emphasizes the importance of autonomy, competence, and relatedness as key drivers of motivation and engagement (Ryan & Deci, 2000). Moreover, through serious games, learners are given opportunities to try out different strategies without worrying about the consequences that come with real-world assessments (Gee, 2007). This is especially critical in situations involving CI, where the repercussions of making a mistake could be life-threatening, and where experiential learning leads to the acquisition of adaptive expertise, characterized by the ability to transfer and adapt knowledge to effectively deal with unfamiliar problems (Connolly et al., 2012; Hatano & Inagaki, 1986).

Recent research has also underscored the role of feedback mechanisms in enhancing instructional effectiveness within GBL settings. Real-time, adaptive feedback enables learners to recognize their errors, refine their strategies, and develop stronger problem-solving skills (Clark et al., 2016; Shute, 2008). Shute (2011) further demonstrated that embedding formative assessments seamlessly within game environments, referred to as "stealth assessment," allows for continuous, unobtrusive monitoring of learner progress, which in turn supports the delivery of timely and personalized learning interventions. Beyond serving as complementary means for acquiring knowledge and cognitive skills, the integration of immersive technologies such as virtual reality (VR) and augmented reality (AR) into serious games has enabled high-fidelity recreations of real-world scenarios, thereby providing learners with rich, situated experiences that transfer effectively to their actual work environments (Makransky& Petersen, 2019; Radianti et al., 2020).

3.2. Decision-Making in High-Risk Environments

Decision-making in CI contexts is inherently challenging due to the complexity, uncertainty, and high stakes involved (Rehak et al., 2019; Zio, 2016). During the operation of these infrastructures, operators must contend with significant uncertainty, acute time pressure, and the fact that CIs typically comprise tightly coupled networks of interdependent systems, where a disruption in one can trigger cascading failures across others (Rinaldi et al., 2001; Ouyang, 2014). Furthermore, operators are required to process large volumes of information, evaluate potential hazards, and make rapid decisions that may have far-reaching consequences for system stability and public safety (Ouyang, 2014; Pescaroli& Alexander, 2018).

Traditionally, decision-making models have tended to portray individuals as rational agents. However, research in cognitive psychology has demonstrated that decision-making, particularly in high-risk situations, is significantly influenced by cognitive biases, heuristics, and emotional responses (Tversky & Kahneman, 1974; Kahneman, 2011). Under conditions of stress and uncertainty, individuals tend to resort to simplified decision strategies, which can lead to suboptimal outcomes (Starcke & Brand, 2012). Serious games offer an effective means of addressing these challenges by simulating complex conditions and providing individuals with opportunities to practise decision-making within realistic scenarios (Connolly et al., 2012; van der Hulst &Ruijsendaal, 2014). Moreover, serious games can incorporate elements such as uncertainty, incomplete information, and time pressure, thereby creating authentic experiences that mirror the cognitive demands of real-world operations (Hamari et al., 2016). Importantly, serious games also facilitate the development of critical competencies such as situational awareness, risk assessment, and adaptive thinking (Endsley, 1995; Lopes &Bidarra, 2011).

Situational awareness plays a central role in decision-making within CI systems. Endsley's (1995, 2017) three-level model describes how operators must perceive relevant environmental cues, comprehend the current situation, and project future states. Serious games enhance situational awareness by presenting dynamic scenarios that require continuous tracking, interpretation, and anticipation of system states. In addition, serious games facilitate collaborative decision-making through multi-agent interactions. Since most CI operations involve coordination among different stakeholders, including engineers, emergency responders, and policymakers, multiplayer serious games can simulate these interactions and allow participants to practise communication and coordination skills (Comfort et al., 2010; Salas et al., 2008).

Resilience thinking represents another vital dimension of CI management, encompassing the ability to anticipate, withstand, adapt to, and recover from the effects of disruptions (Hollnagel, 2014; Woods, 2015). Serious games can simulate scenarios involving cascading failures and system interdependencies, enabling learners to understand the pathways through which disturbances propagate across interconnected systems and to evaluate how resilience strategies can mitigate their impact (Linkov et al., 2018).

3.3. Cognitive and Behavioral Dimensions of Serious Games

Effective serious game design must account for both cognitive and behavioral dimensions, as learning and decision-making are fundamentally shaped by these factors. According to cognitive load theory, learning is optimized when instructional materials are designed to manage the demands placed on working memory (Sweller, 2011; Mayer, 2019). Complex simulation environments present a significant challenge in this regard, as cognitive overload can adversely affect learning outcomes. It is therefore imperative to design scenarios and interfaces that achieve an appropriate balance between complexity and usability.

Serious games can address this challenge through the gradual escalation of difficulty, allowing players to acquire foundational knowledge before encountering more demanding levels. This scaffolding approach supports cognitive development while preventing overload, thereby enhancing learning (Clark et al., 2016; Plass et al., 2015). Emotional engagement constitutes another essential factor in effective learning. Research in affective neuroscience has demonstrated that emotions profoundly influence attention, memory consolidation, and decision-making (Damasio, 1994; Immordino-Yang & Damasio, 2007).

Recent studies have demonstrated that digital interventions can effectively support emotional regulation, behavioral management, and socio-emotional development in educational contexts, particularly in inclusive and special education settings (Simos, 2025b; Simos &Xyloparkioti, 2025; Simos et al., 2026). Further research in special education and digital learning environments has emphasized the importance of emotional intelligence and socio-emotional skills development through technology-supported interventions (Drigas&Sideraki, 2021; Chaidi &Drigas, 2022; Mitsea et al., 2023). Previous studies have also highlighted the role of games in developing transferable skills and behavioral change (Barr, 2017; Becker, 2017). Through immersive narratives, realistic scenarios, and meaningful consequences, serious games leverage emotional engagement to increase motivation and thereby improve knowledge retention.

Stress is an inherent component of decision-making in high-risk situations. While excessive stress diminishes performance, a moderate level of stress can enhance focus and accelerate decision-making (Driskell & Salas, 1996). Serious games can reproduce conditions of stress in a controlled manner, enabling players to develop coping strategies and improve their performance under pressure (Endsley, 2017). Behavioral change represents one of the most important objectives of serious games. Beyond equipping learners with knowledge, serious games aim to influence attitudes, behaviors, and decision-making processes. Empirical evidence supports the effectiveness of serious games in facilitating behavioral change through experiential learning and the reinforcement of desired behaviors via feedback and reward mechanisms (Graafland et al., 2012).

Furthermore, advances in artificial intelligence (AI) have made it possible to create adaptive serious games that customize learning experiences according to user performance. AI-powered systems can adjust difficulty levels, provide personalized feedback, and simulate intelligent agents, leading to enhanced engagement and learning effectiveness (Makransky& Petersen, 2019; Shute, 2011). The integration of learning analytics within serious games also enables comprehensive evaluation of player performance, facilitating the identification of strengths, weaknesses, and individual learning trajectories. This evidence-based approach supports continuous improvement of both learners and training systems (Clark et al., 2016; Loh et al., 2015).

4. Design Framework for Serious Games in Critical Infrastructure Training

4.1. Core Design Principles for Serious Games in High-Risk Environments

The development of serious games intended for CI training should be grounded in a systematic and interdisciplinary methodology that integrates the fundamental concepts of instructional design, cognitive science, systems engineering, and human-computer interaction. Game design principles have been extensively discussed in prior research, highlighting the importance of structured mechanics, player interaction, and meaningful learning experiences (Salen & Zimmerman, 2015; de Freitas, 2018). In contrast to entertainment-oriented games, serious games designed for high-risk environments should prioritize learning effectiveness, decision-making accuracy, and behavioral transformation over mere engagement (Arnab et al., 2015; Michael & Chen, 2006).

Scenario fidelity, defined as the extent to which the game environment mirrors actual systems, processes, and constraints, constitutes one of the most critical design considerations. A higher degree of fidelity reinforces learner involvement and facilitates knowledge transfer, as learners encounter scenarios that closely resemble real operational contexts (Makransky& Petersen, 2019; Sitzmann, 2011). For CI training, this entails the depiction of system interdependencies, the introduction of cascading failure scenarios, and the use of real-time data feeds (Linkov et al., 2018).Complementing scenario realism, complexity management represents an equally important consideration. This involves balancing the intricate details of a simulation with the level of user-friendliness required to support effective learning. While realistic simulations are essential, excessively complex environments can overwhelm learners and thereby impede learning. According to cognitive load theory, instructional design should seek to optimize the three forms of cognitive load, namely intrinsic, extraneous, and germane, to maximize learning outcomes (Sweller, 2011).

Serious games should therefore introduce increasing levels of difficulty, provide scaffolding mechanisms, and employ intuitive interfaces to enhance user interaction and comprehension (Clark et al., 2016).

Effective serious game design also depends significantly on feedback systems. Feedback that is instantaneous, adaptive, and explanatory enables learners to evaluate the results of their decisions and modify their behavior accordingly (Plass et al., 2015; Boyle et al., 2016; Shute, 2008). In the CI domain, feedback may take the form of performance indicators, system status updates, and simulated consequences of decisions, such as system breakdowns or recovery scenarios.A goal-based design approach is equally important for maintaining learner focus and ensuring alignment with learning objectives. Learners are guided through training stages and their skills are progressively refined through clear targets, tangible outcomes, and well-organized tasks (Deterding et al., 2011). These elements become particularly crucial in environments involving threats to life, where both the accuracy and the speed of decisions matter.Moreover, interactivity and agency are of central importance, as they foster engagement and create meaningful learning opportunities. A serious game should allow users to exert influence over the environment, make consequential decisions, and observe the impact of their actions. Experiencing this action-consequence cycle first hand promotes deeper learning through trial and error (Gee, 2003; Plass et al., 2015).

4.2. Decision-Making-Oriented Game Mechanics

Serious games designed for CI training should incorporate game mechanics that specifically target the development of decision-making competencies. These mechanics must replicate the uncertainties, time pressures, and system interdependencies characteristic of real-world CI operations to provide effective learning experiences (Hamari et al., 2016; Klein, 1998).

Time-pressure mechanics constitute a fundamental component, requiring players to make decisions within strict time constraints. This type of mechanic effectively mirrors real-world conditions where delays can result in the escalation of malfunctions and the amplification of risk. Time pressure also induces cognitive stress, which can influence both decision-making strategies and individual performance (Endsley, 2017; Starcke & Brand, 2012).Uncertainty modeling plays an equally important role. By periodically presenting players with incomplete or ambiguous information, this mechanic encourages the development of risk assessment and probabilistic reasoning skills. Players are placed in situations where decisions must be made without full knowledge of the state of the system (Ouyang, 2014; Tversky & Kahneman, 1974). The inclusion of stochastic elements and random events adds to the realism of the simulation and provides learners with the opportunity to demonstrate their ability to adapt to changing conditions.

Since decision-making in CI contexts is inherently collaborative and often requires the coordinated efforts of multiple parties, multi-agent interaction mechanics facilitate communication, coordination, and negotiation among players in ways that reflect real-world settings (Comfort et al., 2010; Salas et al., 2008). Through such interactions, players practise not only crisis management skills but also essential interpersonal competencies including teamwork and communication.Another significant mechanic is consequence-based learning. Players are exposed to the outcomes of their decisions immediately after making them, including system breakdowns, resource depletion, or successful recovery (Graafland et al., 2012). Observing the consequences of their choices enables players to develop mental models of system dynamics and to understand cause-and-effect relationships. Branching scenarios further support this process by offering learners the opportunity to explore a diversity of strategies and outcomes, thereby fostering critical thinking and strategic reasoning (Connolly et al., 2012).Finally, data-driven performance metrics provide quantitative assessment of player performance, including decision-making accuracy, response timeliness, and system state management. Such metrics enable both learners and instructors to engage in reflective assessment and to identify areas requiring improvement (Sitzmann, 2011; Loh et al., 2015).

4.3. Adaptive Systems, AI Integration and Personalization

The incorporation of AI into serious games represents a significant advancement in training technologies, enabling adaptive, personalized, and intelligent learning environments. AI-powered systems possess the capability to modify game parameters in real time based on user performance, thereby offering customized experiences that lead to enhanced learning outcomes (Makransky& Petersen, 2019; Shute, 2011).For example, AI can be employed for adaptive difficulty adjustment, whereby the game modifies its level of challenge in response to the learner's demonstrated ability. This approach maintains player motivation by ensuring an appropriate level of challenge while preventing frustration or boredom (Hamari et al., 2016; Csikszentmihalyi, 1990). Such adaptive mechanisms can also deliver personalized assessments by identifying key strengths and weaknesses and directing learners toward areas requiring improvement.

AI-enabled intelligent non-player characters (NPCs) and agents that simulate realistic human behaviors are becoming increasingly important in serious game design (Arnab et al., 2015). AI technology can represent different stakeholders, system components, or adversaries, giving rise to dynamic and unpredictable scenarios that enhance the depth and authenticity of the training experience.AI is also capable of supporting predictive analytics, which can be used to project future scenarios by evaluating present decisions. This feature provides learners with the opportunity to reflect on the long-term effects of their choices and to refine their strategic thinking abilities. In the CI domain, predictive models can depict potential component failures and recovery processes, offering valuable insights into system resilience (Linkov et al., 2018; Ouyang, 2014).

Furthermore, learning analytics enable the collection and examination of user data to achieve a detailed understanding of learning processes and outcomes. These insights can be leveraged to refine game design, improve training efficiency, and support evidence-based decision-making in education (Clark et al., 2016; Loh et al., 2015). Recent research also highlights the role of digital technologies in enhancing metacognitive and self-regulation skills, particularly in learners with diverse needs (Mitsea et al., 2022; Pergantis et al., 2025).Personalization is a further hallmark of AI-powered serious games. Such games can adapt content, scenarios, and feedback to accommodate the particular needs of individual learners, thereby addressing a range of learning styles, preferences, and expertise levels (Makransky& Petersen, 2019). Emerging technologies such as digital twins and real-time simulation systems are further extending the scope of serious games. Digital twins enable the creation of virtual replicas of physical infrastructure, facilitating data-driven and highly realistic training environments (Feng et al., 2020). These innovations point toward a future in which serious games for CI training achieve unprecedented levels of fidelity and pedagogical effectiveness.

5. Applications, AI Integration, and Evaluation in Critical Infrastructure Training

5.1. Applications of Serious Games in Critical Infrastructure Domains

Across a wide array of CI domains, serious games are increasingly serving as tools for enhancing preparedness, decision-making, and system resilience. These domains include energy, transportation, healthcare, emergency management, and cybersecurity, all of which are characterized by high levels of complexity and risk (Linkov et al., 2018; Kröger, 2019).

In the energy sector, serious games have been used to simulate grid breakdowns, cyber-physical attacks, and load-balancing challenges. Operators are able to analyze vulnerabilities and evaluate countermeasure strategies under conditions that closely approximate reality (Ouyang, 2014). These simulations map the interdependencies of different infrastructure elements, depicting cascading failures and resilience mechanisms (Pescaroli& Alexander, 2018; Rinaldi et al., 2001).The field of disaster response and emergency management has likewise benefited substantially from serious games. Participants engage in decision-making under crisis conditions that incorporate time constraints, multiple stakeholder involvement, and inherent uncertainty. Research indicates that such simulations enhance both individual and team performance, particularly with respect to coordination in complex and rapidly evolving situations (Comfort et al., 2010; Salas et al., 2012).

Healthcare applications of serious games are concentrated primarily at the level of emergency response training, patient triage, and crisis management. By simulating critical decision points, such games enhance the technical and non-technical skills of practitioners (Graafland et al., 2012). In the cybersecurity domain, serious games address functions such as threat detection, risk assessment, and incident response. These games expose users to a variety of potential cyber-attacks and countermeasures, thereby enhancing situational awareness and fostering strategic capabilities in volatile environments (Dunn Cavelty, 2020; Bodeau et al., 2017).Transportation systems represent another major area of application, with serious games being used to simulate traffic management scenarios, infrastructure disruptions, and inter-agency coordination. Decision-makers benefit from these simulations, which provide a deeper understanding of system dynamics and assist in improving operational efficiency under stress conditions (Kröger, 2019).Overall, the deployment of serious games across CI domains demonstrates their versatility and efficacy as training tools. Their capacity to simulate complex systems, deliver experiential learning, and support decision-making renders them particularly well-suited for high-risk environments.

5.2. Artificial Intelligence and Emerging Technologies

The integration of AI and emerging technologies into serious games has profoundly enhanced their potential as training tools. AI-augmented serious games are evolving into intelligent, adaptable training systems capable of personalizing the learning environment, adjusting scenarios in real time, and even anticipating player behavior (Makransky& Petersen, 2019).

Adaptive learning systems represent one of the most transformative developments in this area. These systems monitor player performance and dynamically adjust game conditions, scenarios, and feedback to maintain an optimal balance between challenge and support (Hamari et al., 2016; Csikszentmihalyi, 1990). AI is also central to the creation of intelligent agents and non-player characters (NPCs) that exhibit behaviors, interactions, and decision-making processes closely approximating those of humans, thereby providing players with realistic and unpredictable experiences. In the context of CI training, such agents can represent system components, adversaries, or diverse stakeholders, enriching the interaction model (Arnab et al., 2015).In the area of predictive analytics, AI enables virtual environments to simulate future scenarios based on the decisions made by the player. This is particularly valuable in the CI context, where predictive models can generate scenarios involving cascading failures, recovery efforts, and system resilience evaluation (Linkov et al., 2018). Technologies such as virtual reality (VR) and augmented reality (AR) further enhance the training experience by providing heightened levels of presence and embodiment, enabling users to physically manipulate virtual objects and establish a strong connection with the simulated environment (Makransky& Petersen, 2019; Radianti et al., 2020).

Digital twins, which are virtual replicas of physical systems fed by real-time data, offer the potential to create exceptionally realistic simulations that are tightly coupled to their real-world counterparts (Feng et al., 2020). Serious games that incorporate digital twins can yield highly satisfactory results in training and decision support. Finally, learning analytics and data-driven methods enable the collection and processing of detailed performance data, shedding light on user behavior, learning trajectories, and decision-making patterns. These data can be used not only for evaluating training effectiveness but also for informing the ongoing development of training systems (Clark et al., 2016; Loh et al., 2015).

5.3. Evaluation and Effectiveness of Serious Games

The evaluation of serious games is essential for confirming their training effectiveness. Evaluation models typically consider the achievement of learning objectives, changes in behavior, user involvement, and system effectiveness (Sitzmann, 2011; Kirkpatrick & Kirkpatrick, 2016). The most widely employed method involves the assessment of cognitive outcomes, including knowledge acquisition, problem-solving skills, and decision-making accuracy. Empirical evidence indicates that serious games can significantly enhance these skills when compared with more conventional training methods (Wouters et al., 2013; Boyle et al., 2016).Behavioral outcomes also merit equal attention. Serious games are intended to influence learners' actions in real-world situations, and behavioral change may manifest as skills development and improved decision-making effectiveness. Research supports the view that experiential learning environments are among the most effective means of effecting behavioral change (Graafland et al., 2012; Barr, 2017).

User engagement and motivation are also critical indicators of effectiveness, as they strongly influence learning persistence and outcomes. Due to their interactive and immersive nature, serious games tend to be more engaging than traditional methods (Hamari et al., 2016; Ryan & Deci, 2000). Transfer of learning, defined as the learner's ability to apply knowledge and skills acquired in the game environment to novel real-world situations, represents another important metric. Transfer is considerably enhanced by high-fidelity simulations and realistic scenarios (Sitzmann, 2011; Salas et al., 2012). Case-based research further supports the effectiveness of digitally supported interventions in addressing complex cognitive, emotional, and behavioral profiles in educational environments (Simos, 2026; Simos, 2025c).

Performance can also be assessed through quantitative metrics such as reaction time, decision accuracy, and system reliability, which provide an objective picture of both individual and team performance (Clark et al., 2016). Finally, mixed-method approaches that combine quantitative and qualitative data are increasingly being used to evaluate serious games. These approaches offer a comprehensive understanding of learning processes and outcomes, supporting the continuous improvement of training systems (Creswell & Plano Clark, 2018).

6. Conclusions

Critical infrastructures are becoming increasingly complex, interconnected, and exposed to diverse threats. Training decision-makers effectively for these high-risk, unpredictable, and rapidly changing environments demands advanced and innovative educational methodologies. The limitations of traditional training methods, which often fail to prepare individuals adequately for the cognitive, behavioral, and systemic challenges involved in managing contemporary infrastructures, are well documented (Linkov et al., 2018; Kröger, 2019; Salas et al., 2012). Under such circumstances, GBL and serious games have emerged as transformative educational instruments that bridge the gap between theoretical learning and practical experience while fostering the development of essential competencies.

This research has demonstrated that serious games facilitate the development of decision-making capabilities by creating immersive and interactive learning experiences in which learners can apply and refine their knowledge (Plass et al., 2015; Wouters et al., 2013). Exposure to challenging situations in games that closely approximate real-world conditions encourages learners to think critically and creatively, exercise leadership and teamwork, and learn to navigate complex and evolving situations effectively (Pescaroli& Alexander, 2018; Ouyang, 2014).

A central contribution of this paper is the proposed framework for developing purpose-built training games for CI. This model integrates fundamental principles of game development, including scenario authenticity, cognitive load management, adaptive feedback, and player engagement, together with cutting-edge elements such as AI, predictive analytics, and personalization (Arnab et al., 2015; Clark et al., 2016). Such an organized approach provides a foundation for creating well-designed games that deliver educational outcomes closely aligned with real-world operational requirements.

The convergence of AI and other emerging technologies introduces a new dimension to serious game design. Adaptive systems that respond to individual learning behavior and progress strongly facilitate learner engagement, while data-driven scenario generation based on analytics makes the learning experience more engaging and effective (Makransky& Petersen, 2019; Hamari et al., 2016). Technologies such as VR, AR, and digital twins offer the potential to create training environments with levels of immersion and realism approaching those of actual infrastructure systems.

Notwithstanding these advances, considerable challenges remain. High-quality games require substantial development costs, diverse expertise, and access to reliable system data. The transferability of simulation-based experiences to real-time decision-making and operational actions remains an issue of critical importance (Sitzmann, 2011). Intensified experimental research is needed to verify the effectiveness of serious games, and hybrid approaches combining simulation-based and real-world training warrant further exploration. The integration of AI and real-time data with gaming platforms also requires continued development.

The implementation of serious games in training programs raises ethical considerations, particularly in the areas of data privacy, system transparency, and potential biases inherent in AI-based systems. As the use of serious games in training programs expands, the establishment of standards, evaluation frameworks, and best practices will be necessary to regulate their development and use.

In conclusion, serious games represent powerful and contextually appropriate training tools that are well-suited to CI environments. Their capacity to simulate complex systems, facilitate hands-on engagement, and enhance decision-making skills has positioned them as important instruments in the development of resilient and adaptive infrastructures. As their capabilities continue to be expanded through technological innovation, serious games are poised to become one of the most significant means of professional development and emergency preparedness education in high-risk sectors.

Compliance with ethical standards

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Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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