



VIRTUAL REALITY TOOLS FOR SUSTAINABLE MINING AND ENVIRONMENTAL MANAGEMENT

Evangelos MACHAIRAS¹, Emmanouil A. VAROUCHAKIS^{1}*

¹*School of Mineral Resources Engineering, Technical University of Crete, Chania, Greece*

DOI: 10.2478/minrv-2026-0048

received – 10.03.2026 / revised – 16.03.2026

accepted – 08.05.2026 / published – 22.09.2026

Abstract: The growing demand for Critical Raw Materials (CRMs) requires mining practices that align with sustainability and environmental, social, and governance (ESG) principles, while mining training must adapt through advanced digital tools. This study presents a reproducible Virtual Excursion (VE) workflow for mining education and environmental management, using 360 panoramic acquisition with XPhase Pro S2/X2 and Insta360 X4 cameras, image stitching in Hugin, enhancement in ACDSee, interactive authoring in Pano2VR 7, and dissemination through the Envi-Stat platform. The analysed scenarios cover the mining life cycle, including underground and surface extraction, processing and conveyor transportation, pit-lake rehabilitation, reforestation, final disposal of non-hazardous sterile material, and in-situ recovery. Beyond immersive visualization, the framework integrates high-resolution panoramic image processing to extract quantitative geometric characteristics of mining features, with a focus on pit lakes, and validates image-based estimates against field surveys and mine-closure documentation. The main benefits are improved spatial understanding, safer pre-fieldwork and safety training, enhanced sustainability literacy, and scalable access to site-specific knowledge. Current limitations include hardware and software costs, the need for high-quality panoramic data and field metadata, specialist skills for content production, possible user discomfort, and the requirement for structured pedagogical adoption. The proposed workflow offers practical directions for integrating VR into mine planning, safety induction, environmental monitoring, closure evaluation, and ESG-compliant training

Keywords: Virtual Reality; Machine Learning; Pit Lakes; Sustainable Mining; Image Processing; ESG

1. Introduction

The accelerated global transition toward clean energy systems, digital infrastructure, and advanced manufacturing has brought Critical Raw Materials (CRMs) to the forefront of strategic concerns for policymakers, industry leaders, and academic institutions. CRMs, including rare earth elements, lithium, cobalt, and other technologically essential minerals, are indispensable for renewable energy technologies such as wind turbines and photovoltaic panels, for the batteries that power electric vehicles, and for a wide range of high-tech applications. At the same time, their supply chains are vulnerable to geopolitical tensions, trade restrictions, and the environmental and social challenges associated with mining. The European Union, through initiatives such as the European Green Deal and the Critical Raw Materials Act, has recognized that sustainable access to CRMs is not merely a question of economic competitiveness but also one of strategic autonomy and environmental responsibility. Addressing these challenges requires innovative engineering approaches, a skilled workforce, and educational frameworks capable of preparing geoscientists to navigate the complex intersection of technological demand, environmental protection, and societal expectations.

In this context, Virtual Reality (VR) has emerged as a promising educational and professional tool that can fundamentally reshape mining engineering and geoscience training. The integration of VR into academic curricula responds to the dual imperative of equipping students with practical, industry-aligned skills and ensuring that these skills are developed in ways that prioritize safety, sustainability, and efficiency. VR allows students to experience mining environments virtually, simulating real-world conditions without the associated risks or logistical challenges of physical site visits. This capability has profound implications for education, as it bridges the traditional gap between theoretical classroom instruction and experiential fieldwork, offering immersive, interactive, and scalable learning environments [1, 2].

* Corresponding author: Emmanouil A. Varouchakis, School of Mineral Resources Engineering, Technical University of Crete, Chania, Greece, evarouchakis@tuc.gr

The origins of VR in mining and geoscience education can be traced to the experimental systems of the 1990s and early 2000s, when researchers began exploring immersive visualization to present geological data and mining operations in novel formats. At that time, VR was limited by technical constraints, including low graphic resolution, latency, and the high cost of hardware. Nevertheless, the promise of these early prototypes lay in their ability to represent spatial data interactively, a feature that traditional 2D maps and static diagrams could not replicate [2]. The following decades witnessed significant improvements in both hardware and software, from motion-tracking systems and haptic controllers to photorealistic rendering engines, creating conditions for VR to move from research laboratories into practical applications across multiple disciplines, including mining [1].

Mining engineering, as a discipline, is uniquely suited to benefit from VR technologies because of its reliance on spatial reasoning, safety awareness, and the integration of geological, geotechnical, and process engineering knowledge. Traditional training in mining has often depended on physical site visits, which are invaluable but also costly, time-consuming, and potentially hazardous. Moreover, access to operating mines is becoming increasingly restricted due to safety regulations, liability concerns, and the confidential nature of industrial operations. In this environment, VR offers a powerful alternative. Immersive environments can replicate underground tunnels, open-pit quarries, processing plants, and rehabilitation areas, allowing students to explore these contexts safely and repeatedly. Through VR, learners can observe and interact with machinery, geological formations, and process flows that would otherwise be inaccessible. As Strzałkowski et al. [1] argue, VR applications in mining and civil engineering have already demonstrated their potential to supplement traditional practices, creating conditions for a new pedagogy of experiential, digitally mediated learning.

The pedagogical benefits of VR have been highlighted across multiple studies. Bellanca et al. [2] emphasized the use of VR environments in mining research to simulate hazardous scenarios and study human responses to risk in controlled conditions. Their work showed that VR could serve as both a research tool and a training medium, particularly in understanding behavioral aspects of mine safety. Similarly, Stothard and Laurence [3] demonstrated the application of large-screen immersive visualization systems to communicate principles of sustainable mining practices, underscoring VR's role not only as a technical training platform but also as a tool for promoting environmental awareness and social responsibility. These early contributions illustrate that VR is not limited to technical replication but also enables the communication of broader concepts, such as sustainability and risk perception, in ways that traditional lectures cannot achieve.

Subsequent studies further validated VR's effectiveness across diverse learner groups. Pedram et al. [4], for instance, investigated the influence of age and industry experience on VR-based mines rescue training, finding that both novice and experienced participants benefited from the immersive format. The study highlighted that VR training outcomes were not significantly constrained by prior exposure to mining, suggesting that VR is a flexible educational medium applicable across a range of audiences. This adaptability is particularly important in higher education, where classrooms often include students with varied backgrounds in geology, engineering, or related sciences. By offering intuitive, spatially grounded experiences, VR ensures that learners can build conceptual understanding regardless of prior field exposure.

The technical feasibility of VR in mining has also been strengthened by advances in user interface devices. Kim and Choi [5] compared performance outcomes across different control devices used in VR mining software, demonstrating that the design of input systems significantly affects user interaction, engagement, and efficiency. Their findings underscored the need for ergonomic, intuitive interfaces to maximize the educational impact of VR. In parallel, Stothard et al. [6] highlighted the potential of mixed reality simulations for sustainable mining, combining VR with augmented reality (AR) and other digital tools to create hybrid environments that merge physical and virtual experiences. These insights point to the evolution of VR beyond isolated applications, toward integrated ecosystems of digital tools that can support both education and professional practice.

Collectively, the literature suggests several key advantages of VR in mining education. First, VR enhances spatial understanding by presenting three-dimensional geological and engineering contexts that are otherwise abstract in 2D. Students can visualize ore body geometries, fault systems, and mine layouts, strengthening their ability to interpret data and make decisions. Second, VR improves safety training by simulating hazardous conditions, such as rockfalls or equipment failures, that cannot be safely reproduced in the field. By rehearsing responses in virtual environments, learners develop muscle memory, situational awareness, and confidence that can translate to real-world scenarios [2, 4]. Third, VR provides cost-effective access to field experiences. As noted by multiple authors, the financial and logistical challenges of arranging site visits often limit opportunities for students; VR reduces dependency on physical access, allowing institutions to extend practical exposure even in resource-constrained contexts [1, 3]. Finally, VR supports interdisciplinary learning by linking mining engineering with computer science, human factors research, and environmental studies, broadening the horizons of geoscience education [6].

Despite these benefits, the literature also acknowledges challenges. Technical limitations remain, including high initial costs for hardware and the need for specialized expertise to create high-quality VR content. The potential for motion sickness or accessibility barriers among certain students must be considered in deployment strategies [5]. Pedagogically, there is a risk of over-reliance on virtual environments at the expense of essential hands-on experiences in real mines. As Stothard et al. [6] suggest, VR should be viewed as a complement rather than a substitute for physical engagement, integrated thoughtfully into curricula to reinforce rather than replace traditional learning. Furthermore, the sustainability of VR initiatives depends on continuous investment, curriculum alignment, and collaboration between academia, industry, and policymakers.

Building upon this foundation, initiatives such as the IMMERSE project and the Envi-Stat platform represent the next stage of VR's integration into mining education. IMMERSE focuses specifically on CRMs, aligning immersive training tools with the European Union's clean energy and sustainability goals. By developing Virtual Excursions that replicate the mining, processing, and rehabilitation of CRMs, it ensures that students are trained not only in technical processes but also in the environmental and social responsibilities of modern mining. Complementarily, Envi-Stat serves as a repository and dissemination platform for VEs, broadening access across institutions and enabling collaborative, open-access digital education. These initiatives embody the trajectory anticipated in earlier literature [1, 2, 3, 4, 5, 6], moving VR from experimental applications to fully integrated, scalable educational infrastructures.

In conclusion, the combined body of literature affirms that VR is a transformative tool for mining and geoscience education, offering immersive, safe, and cost-effective training opportunities that align with sustainability imperatives. By situating VR within the urgent context of CRM supply and environmental responsibility, recent projects like IMMERSE and Envi-Stat demonstrate the relevance of VR not just as an educational novelty but as a strategic response to global challenges. The next sections of this paper build on these insights, presenting the methodology, results, and discussion of VR integration in mining curricula, with a focus on its contribution to sustainable CRM exploitation.

2. Materials and Methods

The development of Virtual Excursions (VEs) followed a structured workflow that blends rigorous field acquisition, reproducible image processing, careful VR authoring, and intentional pedagogical integration. Field teams first conducted site reconnaissance to map vantage points that capture the operational sequence and the geotechnical or environmental context of interest (e.g., excavation fronts, ore-handling nodes, comminution modules, rehabilitation plots). Imagery acquisition relied on 360° panoramic cameras capable of high-resolution, low-noise capture under variable illumination. In practice, the XPhase Pro S2/X2 platform was favored for static, high-fidelity panoramas that would later anchor explanatory overlays, while the Insta360 X4 was used when flexibility, rapid repositioning, or video capture of short operational sequences was required [7, 8]. For subsurface scenes, additional lighting protocols and exposure bracketing were employed to mitigate harsh contrasts and to preserve texture detail around supports, discontinuities, and equipment.

Raw captures underwent a two-stage post-processing pipeline. First, orientation calibration and stitching were performed to produce geometrically consistent equirectangular panoramas. This step relied on Hugin, which allowed precise control over lens parameters, control points, and seam optimization; careful use of Hugin's optimizer minimized parallax artifacts common in confined underground headings and around near-field objects [9]. Second, radiometric adjustments and clarity enhancement were applied in ACDSee to normalize color rendition across sequences, reduce haze, and bring out lithological textures and surface features essential for geotechnical or process interpretation [10]. Where capture conditions varied across a site visit, batch profiles were created to ensure tonal and color consistency within each VE.

Authoring and interaction design were implemented in Pano2VR 7, selected for its robust hotspot logic, node graphing, and multi-device output that preserves smooth navigation on head-mounted displays and standard browsers alike [11]. In this phase, each panorama or video node was annotated with layered content: (i) text callouts describing geological structures (bedding, joints, faults) and process equipment (e.g., crushers, mills, flotation cells); (ii) vector overlays indicating geotechnical elements (support patterns, bolt arrays, mesh) or process flows (from primary crushing to secondary grinding); and (iii) embedded media such as still images of specimens, short voice-over explanations, or schematic diagrams. Hotspot placement followed a "progressive disclosure" principle: core orientation aids and safety-critical annotations appear by default, while deeper technical content remains available on demand, preventing cognitive overload and allowing learners to set their own depth of exploration.

Quality assurance combined technical and pedagogical reviews. A visual QA pass checked stitch integrity, chromatic balance, hotspot hit-boxes, and caption readability at multiple zoom levels and on varied devices. A didactic QA pass—coordinated with in-structors of mining engineering, geology, and environmental modules—validated factual accuracy, ensured alignment with course learning outcomes, and adjusted sequencing so that each VE could stand alone while also reinforcing curricular arcs. Accessibility measures included minimizing abrupt motion between nodes, offering “teleport” movement rather than smooth fly-through in tight spaces, and providing concise alter-native text for key callouts to support screen-reader workflows where feasible.

The resulting VEs were curated and deployed on the Envi-Stat platform, which organizes them by theme across the mining value chain and environmental management. The current portfolio comprises: Underground Mining – Primary Extraction; Environmental Rehabilitation – Reclamation – Remediation; Underground Mining – Primary Extraction – Mining Geology – Geotechnical Engineering; Mining Engineering – Grinding; Processing for Environmental Management Uses; Underground Mining – Geotechnical Engineering; Underground Mining – in-situ Recovery; Mining Engineering – Metal Purification; Surface Quarry Exploitation Management Uses; Environmental Management Reforestation; and Pre-Active Mining.

Surface and Underground Exploitation of CRMs (displaying the Primary Extraction, Mining Geology, Mining and Geotechnical Engineering), Mining Processing (showing the Transportation, Grinding and Beneficiation processes), Environmental Remediation-Rehabilitation-Reclamation (presenting the transition of the previously active mine sites to Rehabilitated Post Mined sites according to the mandatory legal obligations re-specting the Circular Economy’s Principles).

To embed the VEs within instruction, we adopted a course-design pattern that connects each immersive scene to explicit, assessable competencies. In foundation courses (e.g., raw-materials exploitation and mining methods), the Primary Extraction VEs were po-sitioned early to ground vocabulary and spatial reasoning; students practiced identifying excavation geometries, ore–waste contacts, and haulage routes before working problem sets on method selection and productivity. In geotechnical offerings, Underground Mining – Geotechnical Engineering and the extended Mining Geology – Geotechnical Engineering VE were paired with short concept primers on stress redistribution and support design; students used annotated hotspots to reconcile observed support patterns with expected ground conditions, then critiqued alternative reinforcement schemes in brief reflection notes. In processing courses, Mining Engineering – Grinding and Metal Purification supported flowsheet literacy: learners traced material streams through comminution and beneficiation, then linked design choices to energy intensity, recovery, and selectivity. Environmental and closure modules leaned on Environmental Rehabil-itation – Reclamation – Remediation and Environmental Management Reforestation to visualize soil reconstruction, species selection, and monitoring layouts; students compared hotspot documentation to best-practice frameworks and proposed site-specific im-provements. Finally, Pre-Active Mining, Surface Quarry Exploitation Management Uses, and in-situ Recovery anchored discussions on early-stage planning, permitting con-straints, and low-disturbance extraction options.

Evaluation was built in from the outset. After each VE-supported lesson, students com-pleted very short, targeted checks (e.g., locate three features, justify one design choice, identify two hazards and corresponding controls), followed by a five-minute reflection linking the immersive observation to the week’s theoretical construct. Instructors com-pleted brief teaching logs noting where students hesitated, which hotspots required rewriting, and which sequences most effectively primed seminar debate. These data informed quarterly updates to hotspot text, node ordering, and in a few cases, additional captures to close observed “context gaps” (for example, adding an intermediate panorama between primary and secondary grinding bays to make belt routing explicit).

From a technical perspective, the workflow is intentionally reproducible: camera rigs and stabilization practices [7, 8], stitching and calibration conventions [9], enhancement pro-files [10], and interactive authoring templates [11] together form a living methods manual that partner institutions can adopt and adapt.

3. Results

The implementation of Virtual Excursions (VEs) through the IMMERSE project, com-plemented by their curation and dissemination on the Envi-Stat platform, has produced a comprehensive portfolio of immersive learning tools that span the entire life cycle of mining. These results demonstrate the feasibility of developing and integrating VR-based resources into mining engineering curricula and highlight their educational and professional value. The discussion below contextualizes these outcomes with reference to prior research on VR in mining and education, thereby clarifying the significance of immersive approaches for sustainable Critical Raw Materials (CRMs) exploitation.

The results of VE creation can be grouped into three categories: (i) VEs simulating mining operations, (ii) VEs focused on processing and metallurgical stages, and (iii) VEs illustrating environmental rehabilitation and sustainable management practices by adopting the 4Rs Policy, especially in the reuse of by products. Each of these categories addresses specific gaps in traditional mining education while also reflecting the priorities of sustainable development. For example, displaying actual conditions in Underground Mining – Primary Extraction, provides students with an authentic view of excavation practices in ore bodies recognizing the beneficial mining ore and optically separate it from the sterile material, enabling them to grasp the complexity of ore–waste differentiation and material handling. Traditional lectures often struggle to convey the scale and physical constraints of underground headings, whereas immersive panoramas present these realities in a vivid, spatially coherent manner. Similarly, the produced VEs that refer to specific tasks of the Life of Mine (LOM), expand this scope by incorporating geological features, geotechnical parameters, and plenty of technical parameters that should be considered following the sustainable mining practices. VE Underground Mining – Primary Extraction – Mining Geology – Geotechnical Engineering expands this scope by incorporating geological features and ground stability considerations. Here, students can observe bedding planes, discontinuities, and installed support systems in situ, translating textbook concepts of rock mechanics into a spatially meaningful context. These immersive tools directly address the challenge of bridging abstract theoretical knowledge and real-world practice, as identified in earlier studies [1, 3].

On the surface, VEs such as Surface Quarry Exploitation Management Uses allow learners to navigate operational quarries, observing equipment deployment, haulage design, and slope management. This not only supports technical training but also illustrates the broader environmental footprint of surface mining, prompting reflection on land-use conflicts, visual impact, and dust generation. These broader environmental and societal dimensions are essential for aligning mining education with sustainability imperatives, echoing the calls by Stothard and Laurence [3] to use immersive systems for communicating principles of sustainable mining. The inclusion of Pre-Active Mining as a dedicated VE further strengthens this life-cycle approach, drawing attention to the planning and permitting stages of mining. Students can explore baseline studies, site investigations, and stakeholder considerations, cultivating an appreciation for the regulatory and community aspects of project development.

In the realm of processing, the VE Mining Engineering Processing – Grinding provides an immersive introduction to comminution circuits, showcasing crushers, mills, and material flows. While textbooks and lectures describe these processes sequentially, the VR environment situates them spatially, allowing students to appreciate scale, orientation, and workflow continuity. Similarly, Mining Engineering Processing – Metal Purification/Beneficiation demonstrates the transition from ore to refined product, including showing some of the specific beneficiation and metallurgical stages. Here, the combination of panoramic visualization and embedded annotations (internally shown by in-focus points) enables learners to connect abstract chemical and metallurgical principles with their tangible industrial settings. This addresses one of the persistent difficulties in mining education: helping students grasp the integrated nature of extraction and processing systems, rather than perceiving them as disconnected stages. These immersive processing VEs resonate strongly with findings by Strzałkowski et al. [1] and Bellanca et al. [2], who emphasized the potential of VR to represent complex engineering processes in ways that improve understanding and retention.

Equally significant are the VEs dedicated to environmental management, which illustrate how mining can evolve toward greater sustainability. The VE Environmental Rehabilitation – Reclamation – Remediation depicts post-mining landforms under restoration, including soil replacement, slope stabilization, and vegetation strategies. By situating students within these rehabilitated landscapes, the VE emphasizes that mining does not conclude at resource depletion but extends into closure and long-term environmental responsibility. The complementary VE Environmental Management – Reforestation highlights revegetation practices, showing the selection of species, planting schemes, and monitoring approaches. Such immersive depictions resonate with the principle, articulated by Stothard and Laurence [3], that VR can serve as a medium not only for technical education but also for promoting sustainable mining practices. Students gain a holistic appreciation of the mining life cycle, reinforcing the notion that professional responsibility extends to rehabilitation and environmental stewardship.

A particularly innovative VE is Underground Mining – In-situ Recovery, which illustrates a minimally invasive method of extracting minerals by dissolving ore in place and recovering the solution to the surface. This technology, while not yet universally adopted, represents a potential paradigm shift in reducing surface disturbance and environmental impact. By including such emerging technologies within the VE portfolio, the IMMERSE project ensures that students are exposed not only to conventional practices but also to innovative approaches aligned with the future of sustainable mining. This approach is consistent with the view of Stothard et al. [6], who argue that mixed and virtual reality environments should be leveraged to simulate forward-looking, sustainable mining strategies.

The educational impact of these results is best understood through their reception among students and educators. Preliminary evaluations reveal that students perceive VEs as significantly improving their spatial understanding of mining environments. Concepts such as ore body geometry, excavation methods, and geotechnical stability, which often remain abstract in classroom contexts, become tangible when experienced in VR. This finding aligns with the evidence presented by Pedram et al. [4], who reported that VR training improved comprehension across age groups and experience levels. In our case, undergraduate students with limited exposure to fieldwork particularly benefited, as the immersive environments provided them with a form of “pre-fieldwork orientation” that enhanced confidence and reduced anxiety prior to actual site visits. Educators likewise noted that VEs stimulated classroom discussion, with students frequently referencing specific immersive experiences during lectures and tutorials.

From a safety training perspective, VR’s value is also evident. By simulating under-ground and surface environments, VEs allow students to observe potential hazards such as unstable rock masses, confined spaces, or heavy machinery, and to discuss appropriate control measures without exposure to danger. This contributes to developing a safety culture, echoing the arguments of Bellanca et al. [2] and Pedram et al. [4], who emphasized VR’s role in training users to recognize risks and rehearse responses to hazardous situations. Importantly, this safety training is not abstract but contextualized within re-alistic, site-specific representations, increasing its relevance and effectiveness.

Beyond technical and safety benefits, the results demonstrate that VEs can foster an appreciation of the socio-environmental dimensions of mining. By situating students in rehabilitated landscapes or pre-mining planning contexts, VEs encourage reflection on the broader impacts of mining and the responsibilities of engineers. This dimension is crucial for aligning education with contemporary societal expectations of sustainable development. As Stothard and Laurence [3] highlighted, VR’s immersive qualities make it a particularly effective medium for communicating sustainability principles that are otherwise difficult to convey in abstract or quantitative terms.

The discussion of results must also address limitations and challenges. As Kim and Choi [5] showed, user interface design plays a crucial role in determining the effectiveness of VR systems. In our evaluations, some students reported difficulty navigating complex scenes or discomfort during extended sessions, indicating the need for ergonomic controls and thoughtful interface design. Hardware accessibility is another constraint: high-quality VR experiences require robust computing infrastructure and head-mounted displays, which may not be universally available across institutions. While the Envi-Stat platform mitigates this by offering browser-based access to VEs, the full immersive effect often requires dedicated hardware.

Furthermore, the sustainability of VE production poses challenges. Creating high-quality immersive environments requires specialized expertise in image capture, processing, and VR authoring. Institutions with limited resources may struggle to replicate this workflow without external support. This underscores the importance of collaborative projects like IMMERSE, where expertise and resources can be pooled, and of dissemination platforms like Envi-Stat, which provide shared access to finished VEs. As Stothard et al. [6] noted in their discussion of mixed reality simulations, the future of immersive technologies in mining depends on such collaborative ecosystems.

Finally, there is the question of pedagogy. While students value VEs, they must be carefully integrated into curricula to avoid the risk of replacing essential field experiences. VR should complement rather than substitute physical site visits, serving as preparation, reinforcement, or supplementation. As multiple studies have observed [3, 6, 12, 13, 14, 15, 16], the effectiveness of VR depends not just on the technology but on its thoughtful use within broader teaching strategies. In our implementation, this was addressed through alignment with course learning outcomes and iterative feedback from instructors, but further research is needed to establish best practices for curricular integration at scale.

Taken together, the results and discussion demonstrate that the integration of VEs into mining education is both feasible and impactful. By covering the full mining life cycle, from exploration and primary extraction to processing and rehabilitation, the VE portfolio provides students with a holistic, immersive education that aligns with sustainability imperatives and industry needs. The discussion, supported by the existing literature [1, 2, 3, 4, 5, 6], affirms that VR can enhance spatial understanding, improve safety training, reduce logistical barriers, and foster awareness of environmental and social responsibilities. At the same time, it acknowledges that challenges remain in hardware access, content production, and pedagogical integration. These findings reinforce the argument that VR is not an optional supplement but a strategic component of modern mining education, essential for preparing a workforce capable of meeting the challenges of CRM exploitation in a sustainable manner.

Considering the impact of a mining company's Environmental Management technique on Social Approval and the trust gained from each regional Authorized Environmental Inspection Organization, emphasis is placed on the Mining to Closure action plan. Therefore, by deepening cooperation between the scientific representatives from the Technical University of Crete and the administration of the LARCO GMMSA mining company, three VEs demonstrating the implemented Environmental Management practices were created. These VEs provide clear scientific knowledge on this essential subject of study to postgraduate and undergraduate mining engineers.

In all created VEs, info-points are placed at specific locations inside the VE, providing the required information that a trainee should know. Moreover, navigational points have been set according to the correct navigation mapping system, allowing each operator to know the exact location shown in the redirected satellite Google map. The teaching material (including diagrams and written information) has been added to the VE as a pop-up. It is strongly believed that this combined teaching tool directly transfers young engineers to the field, teaching them about on-site conditions and showing the hazards and potential challenges they will face in their future careers. As a result, they will be more ready to provide engineering solutions due to the scientific and experimental knowledge they gain from their graduation.

The first VE focuses on the rehabilitation plan of creating Pit-Lakes in two separately located post-mine areas of the LARCO GMMSA Euboea mine site. It provides clear scientific and technical information for structuring a Pit-Lake, along with details on the environmental monitoring procedures to ensure the efficiency of the Environmental Management action plan. Figures 1 and 2 demonstrate this VE's results.

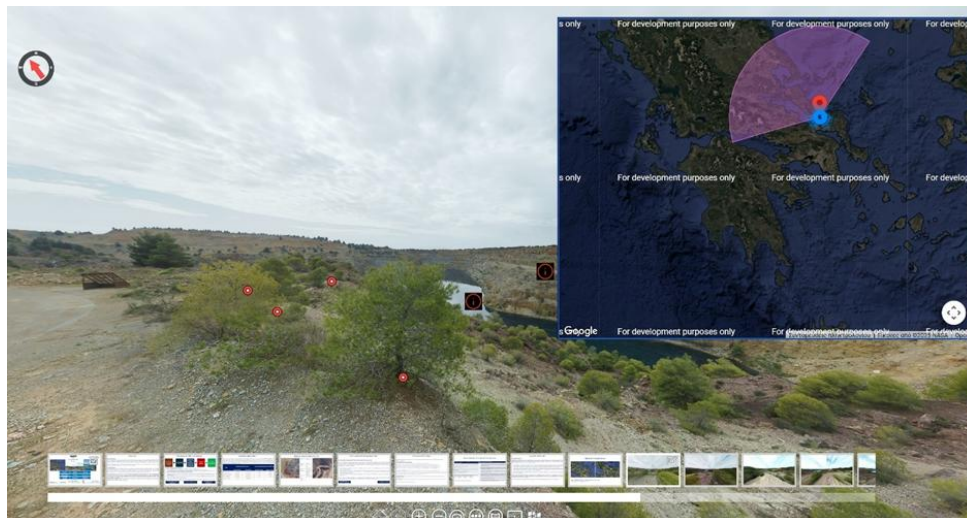


Fig. 1. 360 Panorama captured by the first VE demonstrating the Rehabilitated Area of the Isoma post-mine site at the LARCO GMMSA Euboea mine site, as a Pit-Lake. Red bullet points refer to the navigational points. Grey square with red “i” symbol points refer to the info-points showing the required information at the specific location

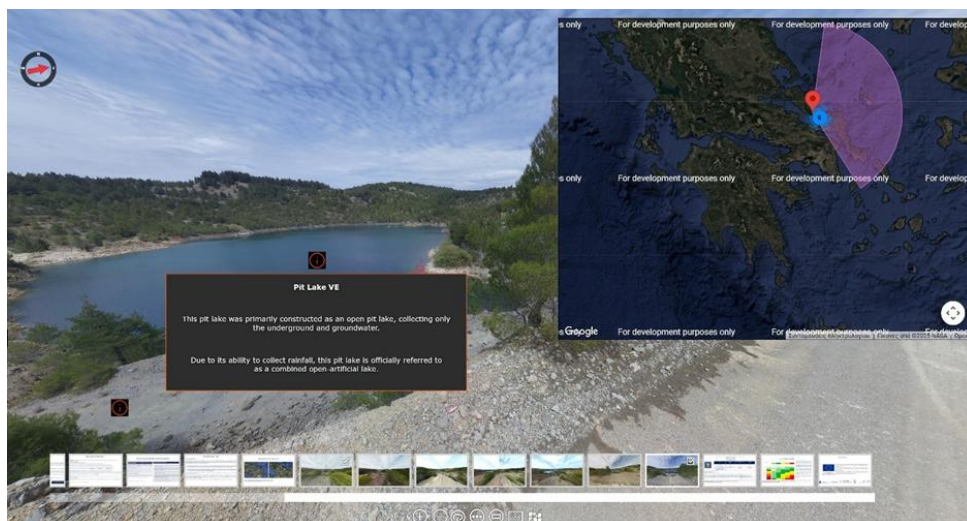


Fig. 2. 360 Panorama captured by the first VE demonstrating the Rehabilitated Area of a northern Isoma post-mine site at the LARCO GMMSA Euboea mine site, as a Pit-Lake. Grey square with red “i” symbol points refer to the info-points showing the required information at the specific location

The second VE focuses on the rehabilitation plan of reforestation in the post-mine area at the LARCO GMMSA Euboea mine site of Isoma. It provides clear scientific and technical information for structuring a reforested zone, along with details on environmental monitoring procedures to identify why reforestation is the indicated solution in specific cases compared to other Environmental Management techniques. Figures 3 and 4 demonstrate VE's results.



Fig. 3. 360 Panorama captured by the second VE demonstrating the Reforested Area of the Southern Isoma post-mine site at the LARCO GMMSA Euboea mine site, as a Replant zone. Blue circles with red “i” symbol points indicate the info-points displaying the required information at specific locations

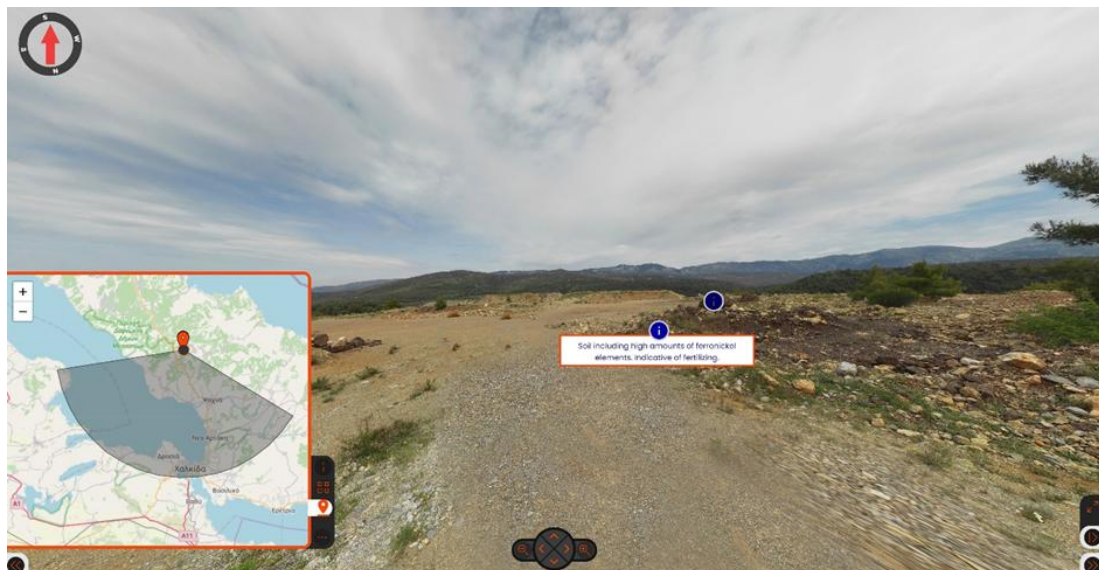


Fig. 4. 360 Panorama captured at the top of the hill, by the second VE, demonstrating the Reforested Area of the Southern Isoma post-mine site at the LARCO GMMSA Euboea mine site, as a Replant zone. Blue circle with red “i” symbol points refer to the info-points showing the required information at the specific location

The third VE focuses on the rehabilitation plan for the final disposal site in a Ferro-Nickel post-mine area at the LARCO GMMSA Euboea mine site. It provides clear scientific and technical information that should be considered before structuring the final disposal site, why it is important, and how it is constructed. It is very important to mention that in cases of non-hazardous sterile material, the final disposal site (of this non-hazardous waste) is an optimal environmental solution. The non-hazardous sterile ore, particularly those containing metal and trace elements, is reused as a fertilizer or filler. So, the young engineers are educated to utilize the non-hazardous sterile waste material, conforming to the Circular Economy's principles expressed through the 4Rs policy. Figures 5 and 6 demonstrate VE's results.

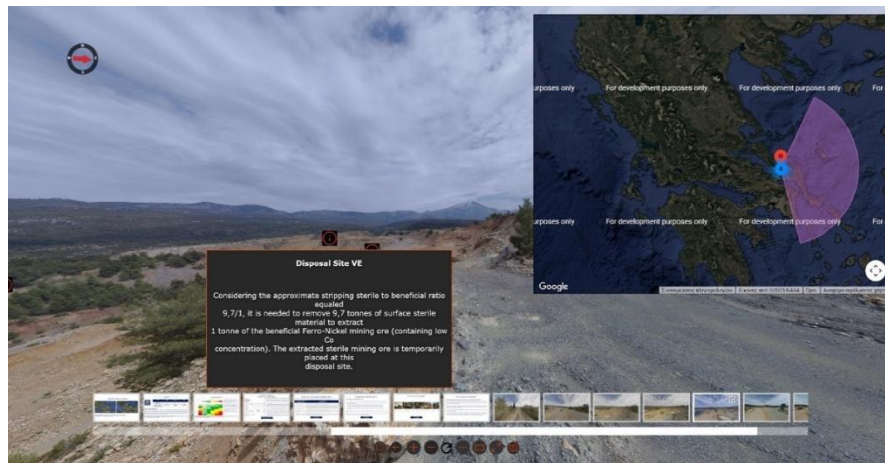


Fig. 5. 360 Panorama captured at the top of the hill, by the third VE, demonstrating the Final Disposal Site Area of the Southern Isoma post-mine site at the LARCO GMSA Euboea mine site. Grey squares with red “i” symbol points indicate the info-points that provide the required information at specific locations

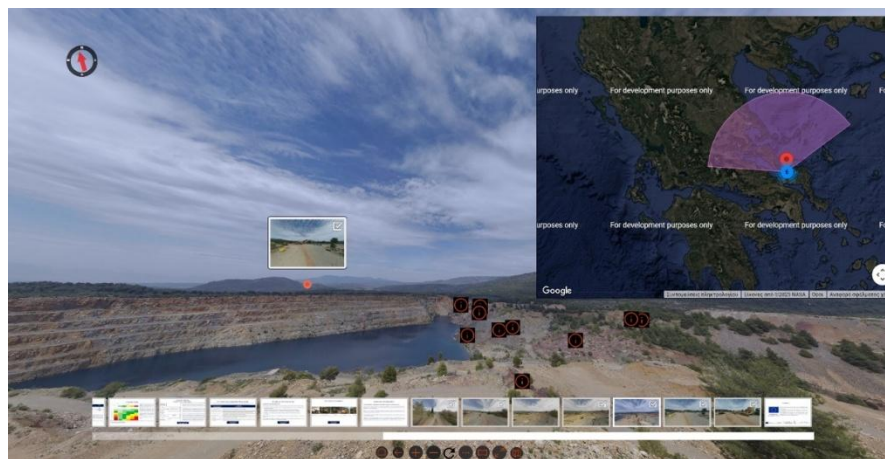


Fig. 6. 360 Panorama captured at the top of the hill, by the third VE, demonstrating the Final Disposal Site Area of the Southern Isoma post-mine site at the LARCO GMSA Euboea mine site. The red bullet point refers to the navigational point, set to show a short preview before clicking. Grey squares with red “i” symbol points indicate the info-points that provide the required information at specific locations

Further indicative results of the Project are provided by the fourth VE demonstrated in Figures 7 and 8, which show the previously active processing stage of the transportation conveyor at the Greek mining company LARCO GMSA's Euboea site. The transportation conveyor belt was used to deliver the primary beneficiated Nickel mining ore from the first grinding unit to the local port to be loaded onto the cargo ship and transported for further beneficiation in Larymna, where the main beneficiation unit is located.

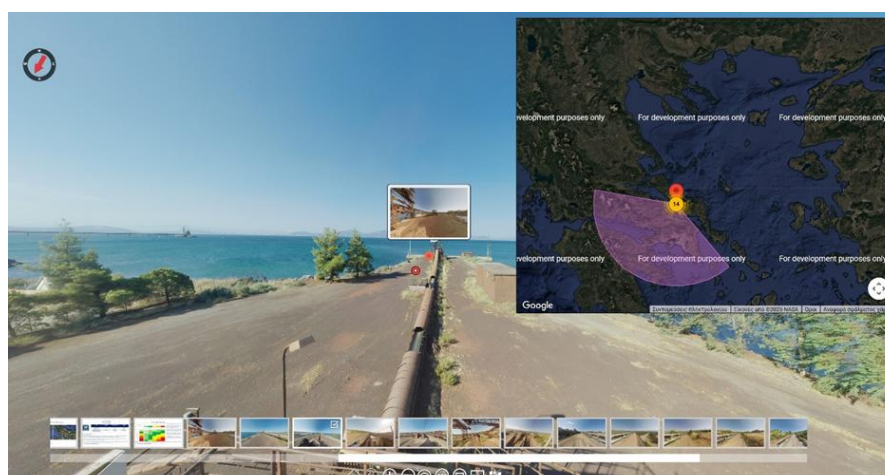


Fig. 7. The 360 Panorama captured at the local port by the fourth VE demonstrates the Ending Point of transportation of the primary purified Ferro-Nickel mining ore to the cargo ship. The red bullet point refers to the navigational point, set to show a short preview before clicking

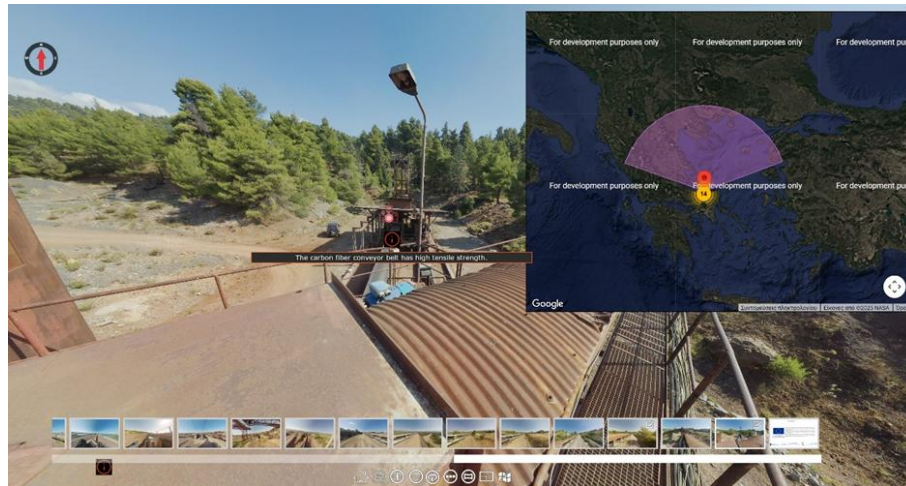


Fig. 8. The 360 Panorama captured at the Starting Point of transportation by the fourth VE shows the main location where the mechanical equipment for the carbon fiber conveyor belt is installed. The red photo icon refers to a pop-up which, when clicked, shows a clear 2D photo of the rollers supporting the transportation

4. Discussion and Conclusions

The integration of Virtual Reality (VR) into mining engineering education, as demonstrated by the IMMERSE project and the Envi-Stat platform, represents a significant step forward in preparing future professionals to meet the challenges of Critical Raw Materials (CRMs) exploitation. The portfolio of Virtual Excursions (VEs) developed covers the full life cycle of mining, from Pre-Active Mining and Primary Extraction through Processing and Metal Purification to Rehabilitation and Reforestation, while also introducing innovative techniques such as In-situ Recovery. By situating learners within these immersive environments, the VEs provide a holistic understanding of mining operations that bridges theoretical instruction and real-world practice. Geological Survey/Exploration-Design-Construction of the actual mine site-Operation (including Primary Extraction, Exploitation, Processing) and Closure (Environmental Management, Reclamation, Remediation, Rehabilitation).

The teaching material contained in the produced VEs regarding the CRMs' mining is not only limited to typical slides including theoretical information, but is placed into specific information-points (info-points) that refer to site-local points. This interactive educational environment permits the students to navigate while exploring the practical application of the theoretical background of the LOM tasks and objectives. Both technical and scientific parameters are combined to enhance the level of engineering.

For instance, as shown in Figures 7 and 8, the students get practical knowledge of one of the most important processing tasks, the transportation of the beneficial mining ore, while at the same time navigating inside this high-dimensional industrial unit that is required for the carbon fiber conveyor belt. Through their navigation, they observe plenty of info points that are localized to specific on-site areas, providing the needed scientific and technical knowledge that upgrades engineering science. By implementing all the created VEs in a variety of different undergraduate courses, it is aimed to provide a primary experimental background combined with the necessary scientific knowledge that makes newly graduated students professionals.

Another key finding, the development of VR technology, which is required for the creation of these VEs, is invaluable for additional engineering fields such as ore beneficiation, mining waste management, and tele-remote operation of the heavy machinery equipment to be used in the primary extraction, etc. Therefore, an additional training target is the creation of virtual reality using the appropriate software and hardware applications, handling them in such a way as to utilize the needed scientific and technical knowledge for teaching purposes. This is the most neuralgic starting point of the future teaching in the new manufactured digitized era.

This innovative mining engineering program of education could be a standard procedure to be implemented at every stage in the LOM to ensure compliance with the Circular Economy's principles and the 4Rs Policy, in close association between universities and mining companies.

Results demonstrate that the proposed VR/VE approach enhances spatial comprehension, reinforces safety training, and strengthens awareness of environmental stewardship across specific mining scenarios, including pit-lake rehabilitation, reforestation, final-disposal design, conveyor transportation, and the visualization of underground, surface, and processing operations. The use of localized info-points, navigational points, pop-up diagrams, and georeferenced panoramic scenes enables students to connect theoretical knowledge with operational conditions, closure obligations, Circular Economy principles, and the 4Rs policy.

In this way, the VEs act as pre-fieldwork preparation, safety-induction material, and a reusable digital record of site-specific engineering practice [1, 2, 3, 4, 5, 6, 17, 18, 19, 20].

The practical benefits of this approach are clear: safer exposure to hazardous or restricted mine environments, improved engagement and confidence among students, reduced dependence on costly field visits, and better communication of ESG-oriented practices to both technical and non-technical audiences. Nevertheless, the application also presents limitations that must be acknowledged. High-quality implementation requires suitable 360 cameras, VR-ready computers or head-mounted displays, licensed or specialized software, reliable internet access for browser-based delivery, adequate field metadata, and trained personnel for image processing, authoring, maintenance, and curricular integration. User adoption can also be affected by motion discomfort, unfamiliar navigation interfaces, limited access to equipment, and the need for instructors to align each VE with explicit learning outcomes rather than treating VR as a stand-alone visualization tool.

Future work should therefore focus on transforming the VE portfolio from an educational demonstration into an integrated decision-support and training ecosystem. Practical directions include linking VR scenes with mine-planning datasets, hazard registers, monitoring records, closure-performance indicators, and environmental-monitoring workflows for pit lakes, reforested areas, final-disposal sites, and processing facilities. In mine planning, VEs can support stakeholder communication, baseline documentation, and scenario comparison before field interventions. In safety training, they can be used for repeated hazard-recognition exercises and emergency-response preparation. In environmental management, they can support periodic visual monitoring, audit trails, rehabilitation assessment, and ESG reporting. Within the framework of the European Union's Critical Raw Materials Act and Green Deal, platforms such as Envi-Stat can extend access to these tools across institutions and industry partners, contributing to a digitally enabled and sustainability-oriented mining workforce.

Acknowledgments

Acknowledgements: The realization of the IMMERSE project has been made possible by funding from the ERASMUS+ grant programme of the European Union (grant number: 2023-1-DE01-KA220-HED-000165332). We are deeply grateful for their invaluable support, which has enabled us to undertake this important endeavor. Their commitment to promoting educational initiatives and intercultural exchange has been instrumental in shaping the trajectory of our project and empowering us to make meaningful contributions to our field.

The dissemination of the expected and produced results conforms with the principles of the Annotated Grant Agreement, Version 1.0 for the EU Funding Programmes within the period 2021-2027. (Link to the source (envi-stat.gr)).

References

- [1] **Strzałkowski P., Bęś P., Szóstak M., Napiórkowski M.**, 2024
Application of Virtual Reality (VR) Technology in Mining and Civil Engineering, Sustainability 16(6): 2239.
doi:10.3390/su16062239
- [2] **Bellanca J.L., Orr T.J., Helfrich W.J., Macdonald B., Navoyski J., Demich B.**, 2019
Developing a Virtual Reality Environment for Mining Research, Mining, Metallurgy & Exploration 36(4): 597–606.
doi:10.1007/s42461-018-0046-2
- [3] **Stothard P., Laurence D.**, 2014
Application of a Large-Screen Immersive Visualisation System to Demonstrate Sustainable Mining Practices Principles, Mining Technology 123(4): 199–206. doi:10.1179/1743286314Y.00000000068
- [4] **Pedram S., Palmisano S., Miellet S., Farrelly M., Perez P.**, 2022
Influence of Age and Industry Experience on Learning Experiences and Outcomes in Virtual Reality Mines Rescue Training, Frontiers in Virtual Reality 3: 941225. doi:10.3389/frvir.2022.941225
- [5] **Kim H., Choi Y.**, 2019
Performance Comparison of User Interface Devices for Controlling Mining Software in Virtual Reality Environments, Applied Sciences 9(13): 2584. doi:10.3390/app9132584
- [6] **Steuer J.**, 1992
Defining Virtual Reality: Dimensions Determining Telepresence, Journal of Communication 42(4): 73–93.
doi:10.1111/j.1460-2466.1992.tb00812.x

- [7] * * *
Stabilizer-Pro. Stabilizer-Pro XPhase-Pro S2/X2 Official Website. Retrieved from <https://www.stabilizer-pro.com/>
- [8] * * *
Insta360. Insta360 X4 Official Website. Retrieved from <https://www.insta360.com/>
- [9] * * *
Hugin. Hugin Official Website. Retrieved from <https://hugin.sourceforge.io/>
- [10] * * *
ACDSee. ACDSee Official Website. Retrieved from <https://www.acdsee.com/en/index/>
- [11] * * *
Garden Gnome. Pano2VR 7 Official Website. Retrieved from <https://ggnome.com/>
- [12] **Sherman W.R., Craig A.B.**, 2003
Understanding Virtual Reality: Interface, Application, and Design, San Francisco, CA, USA: Morgan Kaufmann. ISBN 978-1-55860-353-0.
- [13] **van Wyk E., de Villiers R.**, 2009
Virtual Reality Training Applications for the Mining Industry, In Proceedings of the 6th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, Pretoria, South Africa, 4–6 February 2009; Spencer, S.N., Ed.; Association for Computing Machinery: New York, NY, USA, pp. 53–63.
doi:10.1145/1503454.1503465.
- [14] **Kizil M.S., Kerridge A.P., Hancock M.G.**, 2004
Use of Virtual Reality in Mining Education and Training, In Proceedings of the CRCMining Research and Effective Technology Transfer Conference, Noosa Head, Queensland, Australia, 15–16 June 2004; CRCMining: Brisbane, Australia, pp. 1–7.
- [15] **Stothard P., Squelch A., Stone R., Van Wyk E.**, 2019
Towards Sustainable Mixed Reality Simulation for the Mining Industry, Mining Technology 128(4): 246–254.
doi:10.1080/25726668.2019.1645519.
- [16] **Xie J., Yan Z., Wang X.**, 2023
A VR-Based Interactive Teaching and Practice Environment for Supporting the Whole Process of Mining Engineering Education, Mining Technology 132(2): 89–105. doi:10.1080/25726668.2023.2177737.
- [17] **Assfalg J., Del Bimbo A., Vicario E.**, 2002
Using 3D and Ancillary Media to Train Construction Workers, IEEE MultiMedia 9(2): 88–92.
- [18] **Hamad A., Jia B.**, 2022
How Virtual Reality Technology Has Changed Our Lives: An Overview of the Current and Potential Applications and Limitations, International Journal of Environmental Research and Public Health 19(18): 11278.
doi:10.3390/ijerph191811278.
- [19] **Babalola A., Manu P., Cheung C., Yunusa-Kaltungo A., Da Silva Bartolo P.J.**, 2023
Applications of Immersive Technologies for Occupational Safety and Health Training and Education: A Systematic Review, Safety Science 166: 106214.
- [20] **Strojny P., Dużmańska-Misiarczyk N.**, 2023
Measuring the Effectiveness of Virtual Training: A Systematic Review, Computers & Education: X Reality 2: 100006



This article is an open access article distributed under the Creative Commons BY SA 4.0 license. Authors retain all copyrights and agree to the terms of the above-mentioned CC BY SA 4.0 license.