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D4.2 SkiComCu XR Tools

Project: 23043 – SkiComCu-LL

SkiComCu-Lifelong Learning Course for skills & competences in the Copper sector

Project number:	23043
Project short title:	SkiComCu-LL
Project starting date:	September 2023
Project ending date:	August 2026
Project duration:	36 months

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Internal Identifier:	EITRM122093
Description:	<p>This deliverable documents the first development of the SkiComCu XR learning tools, which constitute a core component of WP4 and complement the digital learning platform described in D4.1. The XR tools have been designed to enrich the learning experience by providing interactive, visual and immersive training resources that support the acquisition of technical skills across the modular curriculum developed in WP3. These applications introduce augmented reality, virtual reality and interactive 3D environments as complementary pedagogical elements, enabling learners to explore material structures, industrial processes and health and safety procedures in a more intuitive and experiential way.</p> <p>The XR tools developed in this first phase include an augmented reality application with a SCORM-compatible version for the examination of crystal structures and defects in copper and its alloys, an interactive module that illustrates the main components and processes of a Peirce-Smith converter, and a virtual reality environment focused on health and safety procedures</p>

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	<p>in mining operations. All tools are designed to integrate seamlessly with the SkiComCu learning platform and to be deployed through standard learning object formats, ensuring compatibility with current, state-of-the-art learning management systems.</p> <p>By offering flexible and engaging training experiences, the XR applications enhance learner motivation, improve conceptual understanding and allow trainees to interact with complex content that is otherwise difficult to visualise through traditional methods. The first development of the XR tools is delivered in month 18 of the project, while further refinements and additional content will continue until month 30 to support the full educational programme and ensure alignment with the final version of the SkiComCu platform.</p>
Included in BP year:	2025
Date:	05/12/2025
Version No.:	V1

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Executive Summary

This deliverable describes the first development of the SkiComCu XR tools, which constitute a core component of Work Package 4. The XR applications were designed to complement the modular curriculum developed in WP3 and to provide learners with interactive and immersive environments that enhance the understanding of complex metallurgical concepts, process operations and health and safety procedures in the mining and copper sectors.

The set of XR applications developed in this first phase includes three main tools. CuExplorer is an augmented reality application, also provided as a SCORM object, that supports the Physical Metallurgy module by enabling users to visualise crystal structures and material defects. Peirce-Smith Converter Inspector is a SCORM-based interactive module that complements the module on the copper supply chain by allowing trainees to explore the structure and functioning of a Peirce-Smith converter and to observe the main steps from matte to blister copper. The third tool is a virtual reality application focused on health and safety procedures in mining environments. This VR application is intended for HMD devices and is currently under development, with completion expected at month 30 of the project.

All XR tools have been conceived to facilitate experiential learning and to provide highly visual, intuitive representations of processes and structures that are difficult to grasp through conventional teaching materials. They will be integrated into the SkiComCu platform documented in deliverable D4.1 and will be accessible to learners as part of their personalised training pathways. This first version provides the functional foundations for the XR components of the project and establishes the basis for further refinement and expansion in the next development cycle.

Objectives, and EIT Impact Framework and KIC Impact

Objectives

Objective	Description	Status
Development of XR-based learning tools that	The objective of this deliverable is to document the first development of	Achieved for the AR and SCORM tools; in progress for the VR

Objective	Description	Status
<p>complement the modular curriculum created in WP3.</p>	<p>the XR learning tools created within WP4. These tools aim to enhance the SkiComCu training programme by introducing interactive and immersive digital resources that support the understanding of key concepts in metallurgy, copper processing and health and safety procedures. The XR applications have been designed to align with the modular curriculum developed in WP3 and to provide learners with complementary visual and experiential learning opportunities that cannot be achieved through conventional materials.</p> <p>The specific objectives of the XR tools are the following:</p> <ul style="list-style-type: none"> To provide interactive visualizations of crystal structures, material defects and other concepts relevant to the Physical Metallurgy module. To support the Copper Supply Chain module with a detailed and interactive representation of the Peirce-Smith converting process and its main components. To introduce a virtual reality environment that allows trainees to practise health and safety procedures in realistic scenarios, improving risk awareness and operational readiness. To integrate all XR tools into the SkiComCu digital platform in formats compatible with standard learning management systems to ensure accessibility, usability and progress tracking. 	<p>application with completion planned for M30.</p>

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EIT Impact Framework and KIC Impact

The XR learning tools developed in this deliverable contribute directly to the objectives of the EIT RawMaterials Strategic Agenda 2021–2027 and align with the broader EIT Impact Framework. By incorporating interactive and immersive digital technologies into the SkiComCu training programme, the project enhances knowledge dissemination, supports skills development and strengthens innovation capacity across the copper value chain.

Strategic Contribution to the EIT Impact Framework:

- **Enhancing digital transformation and innovation in training**
The integration of augmented reality, interactive 3D modules and virtual reality environments introduces advanced pedagogical tools that modernise the way learners engage with technical content. These tools support the adoption of innovative and digital learning methods in the raw materials sector.
- **Supporting workforce development and competence acquisition**
The XR applications facilitate the understanding of complex metallurgical concepts, copper processing operations and safety procedures. They provide experiential learning opportunities that improve knowledge retention and help prepare a more skilled and digitally literate workforce.
- **Strengthening safety culture and sustainable operational practices**
By simulating mining environments and industrial workflows, the tools enable trainees to practise hazard identification, correct safety behaviour and gain insight into operational risks. This supports the strategic goal of promoting safe, sustainable and efficient production practices.
- **Improving inclusiveness and accessibility in EIT RIS regions**
The deployment of XR tools through the SkiComCu digital platform ensures that learners in EIT RIS countries gain access to high-quality and technologically advanced training materials. This contributes to reducing disparities in educational resources and enhances capacity building in regions with limited access to specialised training.
- **Reinforcing the link between education, industry and innovation**
The XR tools complement the modular curriculum developed in WP3 and the platform architecture documented in D4.1. Their integration supports alignment with industry needs, fosters collaboration among partners and strengthens the innovation ecosystem within the raw materials sector.

Impact on EIT RIS KPIs:

- **EITHE08.1 – Participants in non-labelled education activities**
The availability of engaging and interactive XR tools is expected to increase learner participation and completion rates within the SkiComCu programme.

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- EITHE02.4 – Innovations launched on the market
The XR applications constitute innovative learning products that enhance the value of the SkiComCu platform and may be adapted or extended in future KIC initiatives or training contexts.
- KICN01–11 – Improving gender balance in education and training
By providing accessible, flexible and visually engaging learning tools, the XR applications support inclusive training approaches that can help attract and retain a more diverse learner base, including women and underrepresented groups in the raw materials sector.

The platform also contributes to the following long-term impacts outlined in the EIT RawMaterials KAVA framework:

- The development approach, technical foundations and modular design of the XR tools enable replication and adaptation in other sectors, supporting long-term educational innovation and strengthening the capacity-building objectives of the KIC.
- The integration of interactive AR, VR and 3D learning components fosters a culture of continuous digital upskilling, encouraging organisations to adopt advanced training technologies beyond the duration of the project.
- By providing realistic simulations of industrial processes and safety-critical environments, the XR tools help improve long-term operational resilience and support the transition towards safer, more efficient and environmentally responsible practices.
- The creation of high-quality digital learning assets contributes to the establishment of a sustainable educational ecosystem that can evolve over time, integrating emerging technologies and responding to future skill demands in the raw materials sector.
- The modular and interoperable design of the XR tools supports the scalability of the SkiComCu training model, facilitating its integration into broader KIC initiatives and enabling alignment with European strategies for workforce development and industrial innovation.

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1. Outcomes from WP2 and WP3 and Relation with D4.1

The development of the XR tools described in this deliverable builds upon the analytical and pedagogical foundations established in Work Packages 2 and 3, as well as on the technological framework documented in D4.1. WP2 identified the skill gaps and training needs across the copper value chain, highlighting the importance of improving understanding of complex industrial processes, material properties and health and safety procedures. These findings established clear opportunities for the use of interactive and visual learning approaches that can support learners with diverse backgrounds and levels of experience.

WP3 translated the outcomes of WP2 into a modular training curriculum covering mining, copper processing, physical metallurgy, health and safety and soft skills. Several modules identified the need for resources capable of illustrating structures, workflows and operational contexts that are difficult to convey through traditional teaching materials. The XR tools developed in this first phase respond directly to these pedagogical needs. CuExplorer supports the Physical Metallurgy module by enabling learners to visualise crystal structures and defects in copper and its alloys. The Peirce-Smith Converter module provides an interactive representation of the main steps in primary copper production, complementing the Copper Supply Chain module. The virtual reality environment for health and safety allows trainees to practise risk identification and safe behaviour in simulated mining settings.

The XR tools are also closely connected with the digital platform documented in deliverable D4.1. The platform provides the infrastructure through which the XR applications are delivered, accessed and monitored. D4.1 defined the technical environment, user roles and content management workflows that ensure the effective integration of SCORM objects, 3D interactive modules and immersive learning components. The XR tools developed in D4.2 have been designed to align with these requirements, ensuring compatibility with the chosen learning management system, consistent user experience and full integration into the learners' personalized training paths.

By combining the needs assessment of WP2, the pedagogical framework of WP3 and the platform architecture introduced in D4.1, the XR tools contribute to a coherent learning ecosystem that strengthens the overall effectiveness of the SkiComCu training programme. They introduce new modalities of experiential learning that enhance engagement, improve conceptual understanding and contribute to the long-term development of a skilled and digitally literate workforce in the copper sector.

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2. Overview of Developed XR Tools

The first development cycle of the SkiComCu XR tools has resulted in a set of digital applications designed to complement and enrich the modular training curriculum produced in WP3. These tools incorporate augmented reality, interactive three-dimensional environments and virtual reality simulations to provide learners with new ways of exploring concepts, processes and operational scenarios within the copper value chain. The XR tools address learning needs identified in WP2 and extend the functionalities of the SkiComCu digital platform documented in deliverable D4.1 by offering interactive content that supports experiential learning.

Three XR tools have been developed during this phase. The first tool, **CuExplorer**, provides an interactive representation of crystal structures and material defects relevant to the Physical Metallurgy module. It is available in two formats. The augmented reality version allows learners to project and examine three-dimensional crystal models in physical space using a mobile device, while the SCORM-compatible WebGL version offers similar interactions within the learning platform. CuExplorer supports the acquisition of fundamental metallurgical concepts and helps learners visualise structural features that are difficult to understand through static diagrams or text-based materials.

The second tool, the **Peirce-Smith Converter Inspector**, focuses on the copper supply chain and provides an interactive module that illustrates the main components and operational stages of the converting process. By navigating through annotated 3D models and observing process animations, learners can explore how copper matte evolves into blister copper and understand the equipment involved in this transformation. The tool has been designed as a WebGL application packaged in SCORM format to ensure compatibility with the SkiComCu platform and easy integration into the corresponding training units.

The third tool, the **Health & Safety Procedures in Mining** is a virtual reality application that reconstructs a mining environment for training in health and safety procedures. This tool is intended for use with head-mounted displays and allows trainees to move through a simulated workspace, identify hazards and follow correct operational protocols. The VR experience enables a level of immersion and situational awareness that is not achievable with conventional training materials. Although the underlying scenarios and interactions are under active development and are planned for completion in month 30, the current build establishes the foundation for a realistic and engaging safety training module.

Together, these XR tools form a cohesive suite of learning resources that expand the capabilities of the SkiComCu training programme. They introduce interactive and immersive elements that support different learning styles, increase engagement and strengthen the connection between theoretical content and practical understanding. The integration of these applications into the SkiComCu platform ensures that users can access and interact with them as part of their structured learning pathways, making the XR tools an essential component of the digital learning ecosystem envisioned by the project.

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3. Research and Development of XR Learning Tools

The development of the SkiComCu XR applications followed a structured design and implementation process that ensured consistency with the pedagogical requirements of the training curriculum and with the technical specifications of the digital platform introduced in deliverable D4.1. The purpose of this work was to create interactive and immersive tools capable of supporting learners in understanding complex structures, industrial processes and operational safety procedures through visual and experiential approaches.

The XR tools were developed using the Unity game engine, which offers a robust and flexible environment for creating interactive 3D applications and supports deployment across multiple platforms. Unity's modular architecture enabled the integration of 3D models, animations, user interfaces and interaction systems tailored to each educational objective. All XR applications share a common development workflow based on rapid prototyping, iterative testing and adaptation to the learning outcomes defined in WP3.

To ensure compatibility with the SkiComCu learning platform and with standard learning management systems, SCORM-compatible versions of the XR tools were generated using Unity WebGL. This approach makes it possible to deploy interactive 3D content directly through a web interface, enabling seamless integration into the LMS environment and allowing learners to interact with the tools without additional installations. WebGL-based SCORM packages also facilitate progress tracking and learner assessment within the digital platform.

The augmented reality version of CuExplorer was developed using Unity's AR Foundation framework, which provides a unified layer for building AR applications across different devices. For this first development cycle, ARCore was selected as the target technology to ensure full compatibility with Android devices. AR Foundation enabled real-time plane detection, model placement and intuitive interaction with crystal structures and defects, creating an accessible mobile learning experience that complements the SCORM version of the tool.

The virtual reality environment for health and safety procedures was developed using Unity's XR Interaction Toolkit, which provides a standardised interaction system for virtual reality devices. This toolkit supports direct manipulation of objects, locomotion systems, UI interaction and event handling in immersive environments. The VR application recreates typical mining scenarios where learners can explore the workspace, identify hazards and follow procedural steps. Its design allows the gradual incorporation of additional learning scenarios in subsequent development phases.

The combination of these technologies ensures that the XR tools are scalable, maintainable and adaptable to different hardware configurations. The use of a single development engine for all applications provides consistency across the project and facilitates future updates or extensions. This technical foundation enables the creation of high-quality learning experiences that support the long-term objectives of the SkiComCu project.

4. Analysis of Requirements for XR Learning Tools

This section outlines the key functional, technical and pedagogical requirements considered during the design and development of the XR tools. These requirements ensure that the applications support the learning outcomes defined in WP3, integrate with the SkiComCu digital platform described in D4.1 and remain accessible to a wide range of learners within the project.

4.1 Functional Requirements

The XR tools must provide clear interaction pathways that allow learners to explore 3D content, visualise processes and complete guided learning activities. For this first development cycle, the tools must include:

- Interactive manipulation of 3D models including rotation, zoom and object inspection
- Step-by-step guidance for exploring metallurgical processes or safety procedures
- Lightweight interfaces that facilitate intuitive navigation in AR, VR or web-based environments
- Compatibility with SCORM packaging for tools delivered through WebGL
- Ability to run on standard hardware conditions defined by the learning platform

4.2 Technical Requirements

The tools are developed using Unity to ensure cross-platform compatibility and efficient integration with the LMS. The main technical requirements include:

Support for WebGL deployment to generate SCORM packages

- AR functionality based on AR Foundation and ARCore for mobile devices
- VR interactions powered by the XR Interaction Toolkit for HMD experiences
- Optimised 3D assets to ensure smooth performance in AR, VR and browser environments
- Consistent build settings and code structure to facilitate maintenance and future expansions

4.3 Pedagogical Requirements

The XR applications must complement the learning outcomes defined in WP3 by offering visual and experiential representations aligned with the modular curriculum. The main pedagogical requirements include:

- Visualisation of concepts identified as difficult to grasp through static materials
- Guidance mechanisms that support learners with different levels of prior knowledge
- Interaction prompts designed to maintain engagement and improve retention
- Integration with traditional materials such as slides, case studies and assessments within the LMS

4.4 Accessibility and Inclusiveness Requirements

To support learners across EIT RIS regions and diverse training contexts, the XR tools must maintain accessibility standards that allow broad participation:

- Web-based access for SCORM packages without additional installation
- AR tools designed to run on commonly available Android devices
- Clear user instructions and simplified interaction schemes
- Adaptability for use in both self-paced and instructor-supported scenarios

4.5 Integration Requirements with the SkiComCu Platform

The XR tools must integrate smoothly with the digital environment documented in D4.1. Key requirements include:

- Full compatibility with SCORM tracking for WebGL applications
- Simple embedding into course structures, curricula and training pathways
- Consistent metadata, naming and versioning conventions for LMS upload
- Alignment with user roles and permissions defined for learners, educators and administrators

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5. Implementation of the XR Tools

This section presents the implementation details of the three XR tools developed in this first phase. For each tool, the description covers the design approach, the main technical components, the interaction methods and the visual elements that shape the learner experience. The section also includes representative screenshots illustrating the current state of each application.

5.1 CuExplorer

5.1.1 Purpose and pedagogical role

CuExplorer has been developed to support the Physical Metallurgy module of WP3 by providing learners with an interactive and highly visual environment to explore crystal structures and structural imperfections in copper and its alloys. The module addresses concepts such as crystal geometry, atomic coordination, bonding configurations and the different types of lattice defects that influence material behaviour. These concepts are essential to understanding the mechanical, thermal and electrical properties of copper-based materials, yet they are often challenging for learners when presented only through static diagrams or textual explanations.

The tool is available in two complementary formats: a SCORM-compatible WebGL version integrated into the SkiComCu learning platform, and an augmented reality version for Android devices. The SCORM version ensures that learners can interact with crystal models directly within the platform, follow guided tasks and complete evaluation quizzes. The augmented reality version expands on these capabilities by enabling users to place, scale and inspect the structures in physical space, providing a tangible sense of depth, orientation and scale that enhances spatial comprehension.

CuExplorer supports the pedagogical objectives of WP3 by allowing learners to visualise and manipulate a range of crystallographic representations, including pure copper, alloy systems such as brasses, bronzes and aluminium bronzes, and several representative structures extracted from the Materials Project database. This facilitates direct comparison between different crystal systems and compositions, aligning with the curriculum's emphasis on structural diversity and its effect on material properties.

A key feature of CuExplorer is its ability to illustrate different categories of crystallographic defects. Learners can inspect point defects, including vacancies, self-interstitials and foreign interstitial atoms, which play a central role in diffusion, strengthening mechanisms and degradation processes. In the augmented reality version, the tool also supports the visualisation of linear defects, including edge dislocations and screw dislocations. These defects significantly affect plastic deformation and mechanical behaviour in metallic materials. By representing them in an intuitive 3D environment and allowing users to move around the structure, the tool enables a deeper understanding of dislocation geometry.

Through these capabilities, CuExplorer provides a bridge between theoretical learning outcomes and the learner's ability to recognise, interpret and reason about atomic-scale structures. It enhances conceptual

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understanding, supports inquiry-based exploration and helps develop the spatial and analytical skills that are foundational to metallurgical education. The tool therefore contributes directly to learner engagement, comprehension of abstract concepts and the development of skills identified in WP2 as critical for the copper sector workforce.

5.1.2 Design approach

The design of CuExplorer was driven by the need to provide a clear, intuitive and pedagogically effective interface that supports the exploration of crystal structures and defects at different levels of depth. From the outset, the tool was conceived as a dual-format application, with both a SCORM-compatible WebGL version for desktop browsers and an augmented reality version for mobile devices. This dual approach ensures accessibility through the SkiComCu learning platform while also offering an enhanced spatial experience through AR, where learners can visualise atomic structures in their physical environment.

The overall design follows a modular architecture structured around four core interaction domains: material selection, 3D navigation, visualisation control and defect exploration. Each domain is presented to the learner through a dedicated interface panel to minimise cognitive load and ensure that navigation, data inspection and visual customisation remain clearly distinguishable. This organisation reflects well-established UX guidelines for scientific visualisation tools, where transparency of functionality and clarity of feedback are essential to productive learning.

The material selection workflow was designed to ensure that learners engage with a curated set of representative crystal structures before exploring the 3D model. The Materials Database includes pure elements and copper-based alloys, each presented with standardised labels and icons that help learners recognise structural families. The design of this interface emphasises simplicity and encourages comparison between structures, supporting the learning outcomes defined in the Physical Metallurgy module.

Navigation within the 3D environment was designed to be smooth, predictable and consistent across platforms. Orbiting, zooming and panning controls are mirrored between mouse-based and on-screen UI elements, reducing the learning curve for users with limited experience in 3D applications. Camera behaviour was carefully tuned to maintain stability and avoid sudden perspective changes that could disrupt a learner's focus on structural features. In the AR version, the design extends these principles to real-world spatial anchoring, allowing learners to place the model on detected surfaces and walk around it naturally.

The visualisation controls were developed to allow flexible adjustment of structural features. Learners can toggle the visibility of atoms, bonds, unit-cell boundaries, axes and periodic repetitions. Adjustable bond thresholds and atom-size sliders support the investigation of coordination geometries and bonding environments. These tools provide a fine level of control without overwhelming the interface, enabling both introductory learners and more advanced users to tailor the display to their learning needs.

A major component of the design approach involves the representation of defects. The WebGL version focuses primarily on point defects, providing visual markers that help learners distinguish between vacancies, interstitials and self-interstitials. The AR version extends these capabilities to include linear defects, such as

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edge dislocations and screw dislocations, represented using simplified yet scientifically consistent geometries. In both versions, defect controls are grouped into a dedicated panel that allows users to add, remove or modify defect visualisations without altering the underlying structural model. This reinforces the conceptual distinction between the ideal lattice and the imperfections that influence material behaviour.

A task-oriented interaction layer was integrated into the SCORM version to guide learners through a set of structured activities aligned with the learning outcomes of WP3. The checklist system provides explicit goals, encourages exploration and supports formative assessment. Upon completion of mandatory tasks, the LMS automatically unlocks the associated quiz, reinforcing the connection between exploration and evaluation.

In summary, the design of CuExplorer prioritises clarity, flexibility and alignment with pedagogical goals. Its modular interface, dual deployment format and structured interaction pathways ensure that the tool is accessible to learners with diverse backgrounds while offering sufficiently rich functionality to support deeper understanding of crystallographic concepts.

5.1.3 Technical implementation

CuExplorer has been developed as a Unity-based application structured around a single core scene that is adapted for deployment in two formats: an AR mobile application and a SCORM-compatible WebGL module. Both versions share common rendering and interaction logic, implemented using Unity's Universal Render Pipeline (URP) to achieve consistent visual quality, optimised lighting and reliable performance across platforms.

In the AR version, the application uses AR Foundation in combination with ARCore to detect planar surfaces in the user's physical environment. When the system identifies a suitable plane, the interface allows the learner to instantiate one or more crystal structures at user-selected positions on the detected surface. The placement workflow consists of an initial tracking stage, during which AR Foundation continuously evaluates the detected plane, followed by a confirmation stage in which the learner taps on the surface to add a new material. Multiple materials can be displayed simultaneously, allowing users to compare different structures side by side. Each instantiated model includes an on-screen label showing its chemical formula, providing contextual information without requiring additional menus. The AR implementation uses lightweight URP shaders to balance clarity of atomic models with the performance constraints of mobile devices.

The WebGL SCORM version relies on the same core scene but adapts its interaction model to a monitored learning environment that is integrated into the SkiComCu platform. Because the SCORM workflow requires clear task tracking and structured progression, the WebGL version is designed to display a single material at a time. Learners must remove the current model before loading another, ensuring that task completion remains unambiguous and that SCORM tracking variables reflect a controlled sequence of actions. This version embeds SCORM interaction through dedicated plug-ins and JavaScript communication bridges, allowing the LMS to record task completion, progress updates and quiz activation. A custom WebGL template is used to integrate

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the SCORM JavaScript interface, handle fullscreen and windowed view transitions, and manage the responsive layout of the side task panel.

Across both versions, the underlying crystal models and defect structures are generated using a modular architecture in which atoms, bonds, unit-cell edges and defect markers are instantiated dynamically based on data definitions. In the AR version, dislocation geometries (edge and screw dislocations) are displayed as simplified lattice distortions layered onto the atomic grid, enabling the learner to visualise linear defects in spatial context. In the WebGL version, defect visualisation is limited to point defects to maintain clarity within a browser environment and reduce computational load.

Input handling is implemented through a unified camera-controller script that adapts to platform-specific input methods. In AR, camera movement corresponds to the physical motion of the device, while touch gestures enable rotation and scaling of instantiated models. In the WebGL version, camera orbiting, panning and zooming are handled through mouse input and on-screen controls to ensure predictable behaviour for users with varying levels of technical proficiency.

The application's overall architecture was designed to maximise reuse of core components while allowing each version to extend the functionality required by its platform. This modular approach ensures maintainability, simplifies updates and allows for the introduction of additional materials or defect types in future development cycles. The integration with SCORM and the LMS environment also ensures that learner performance, progress and assessment outcomes are captured reliably as part of the SkiComCu digital training ecosystem.

5.1.4 User interaction and functionalities

The interaction model of CuExplorer has been designed to support an exploratory approach to learning, allowing users to navigate freely among different tools and visualisation options according to their needs. The application follows a non-linear interaction structure in both the AR and SCORM versions, with the central scene acting as a hub from which users can access the main functionalities. The flow of interactions for each version is summarised in Figures 1 (AR) and 2 (SCORM).

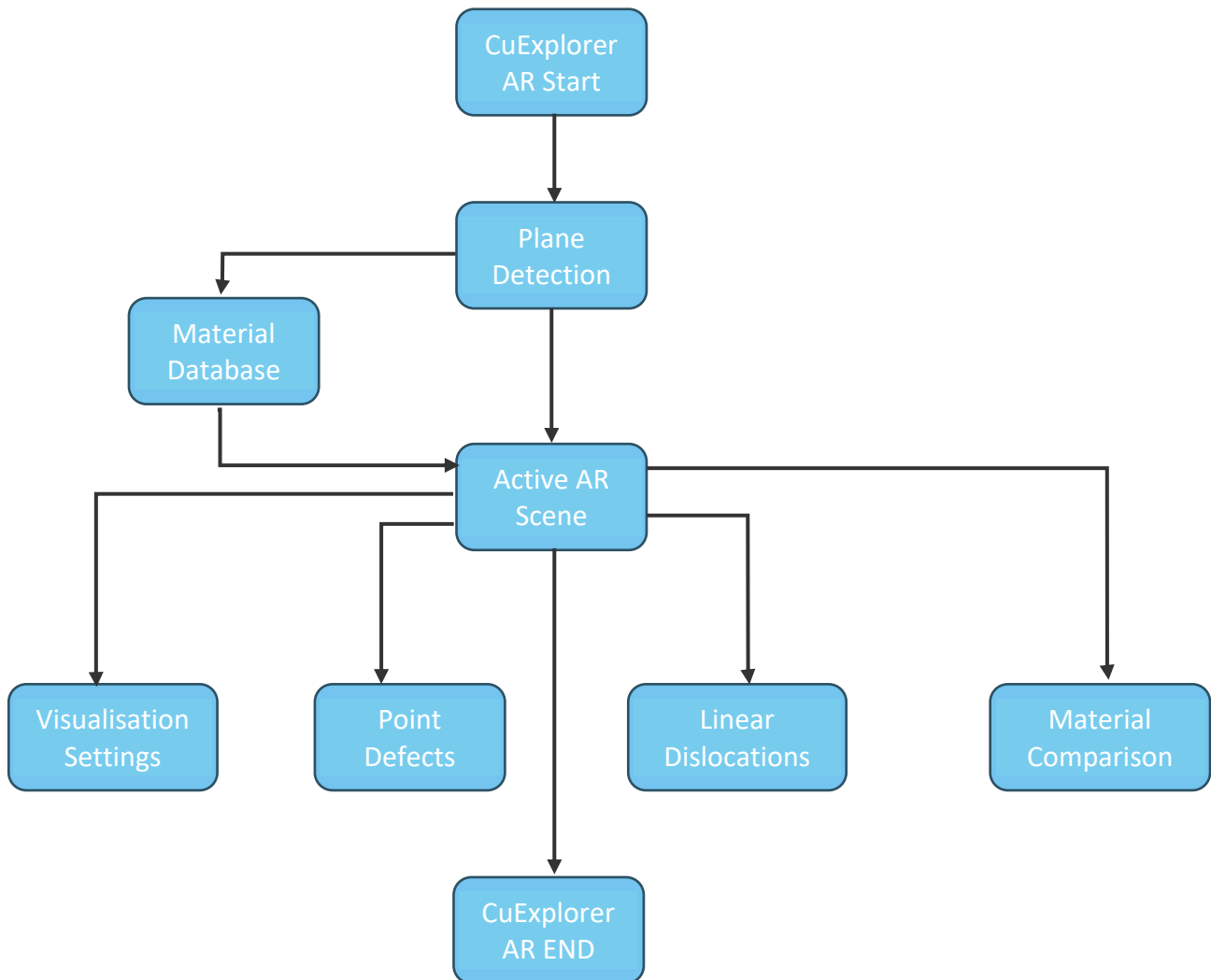


Figure 1. Interaction flow of the CuExplorer AR version.

In the AR version, the user journey begins with the detection of horizontal surfaces in the physical environment. Once a stable plane is identified, learners can open the material database and place one or more crystal structures on that surface. Each structure can then be analysed independently, and learners are free to alternate between several actions without following a predetermined sequence. As illustrated in Figure 1, after inserting a material, users can visualise point defects, activate linear dislocations, adjust visualisation settings, remove or add materials, or compare different structures placed side by side. The active AR scene therefore functions as a central node from which multiple branches of exploration can be followed. Physical

movement around the structures provides an additional dimension of interaction, enabling learners to examine lattice geometry and defect configurations from any angle.

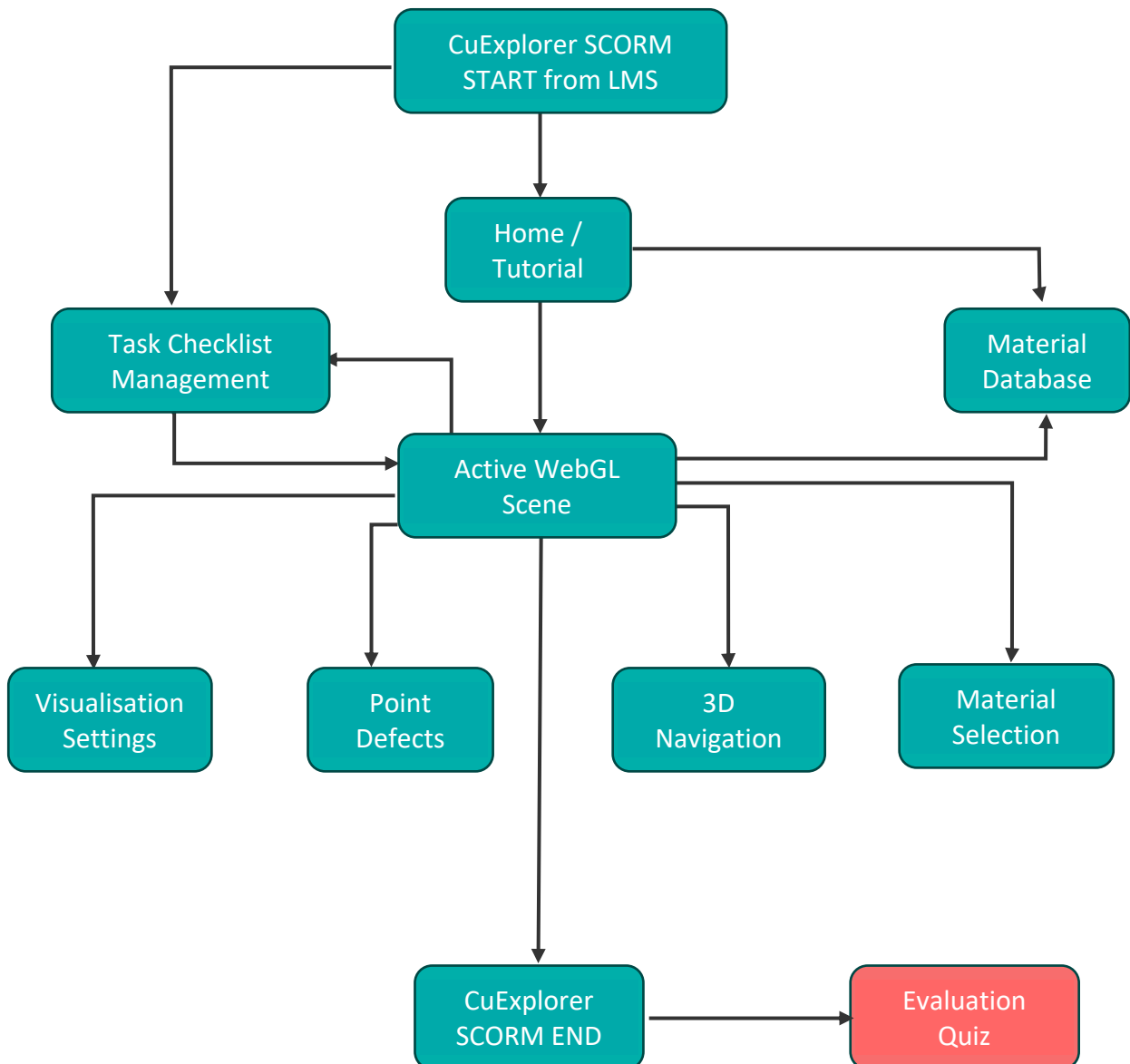


Figure 2. Interaction flow of the SCORM WebGL version.

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In the SCORM WebGL version, interaction is mediated by the structure required for learning management system integration. As shown in Figure 2, the experience begins with a home and tutorial view, followed by the activation of the task checklist, which tracks mandatory and optional actions to be completed during the session. Once the learner enters the active WebGL scene, the interaction becomes non-linear, similar to the AR version, but constrained to a single material at a time. From the central scene, learners can move freely between material selection, 3D navigation, visualisation settings and point defect exploration. These transitions mirror the multi-branch structure depicted in in Figure 2, in which the active scene connects to all available functions and back again.

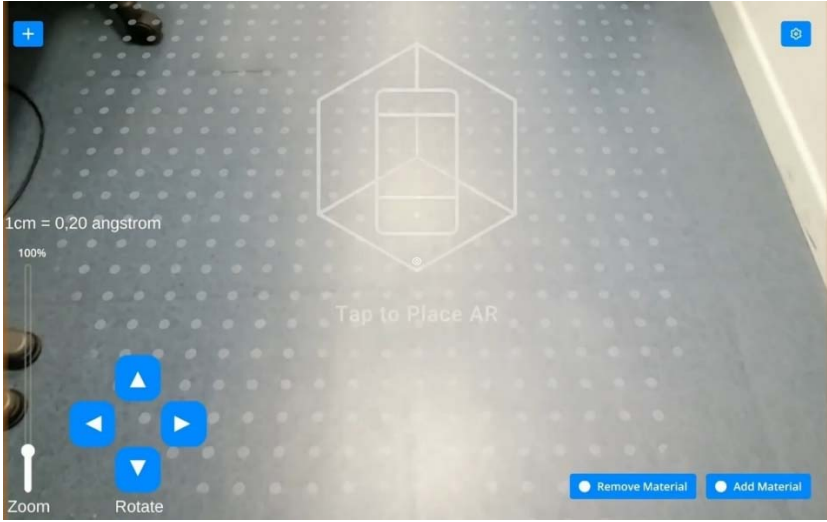
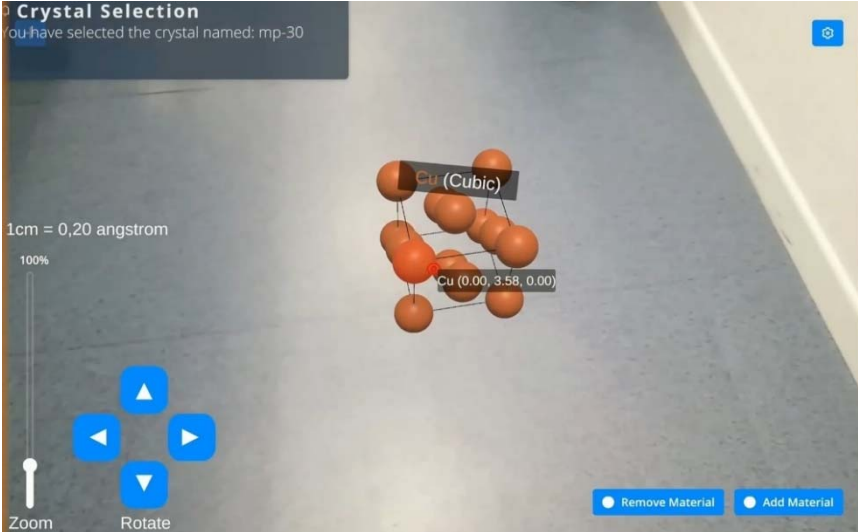
A key difference in the SCORM version is the presence of task management and assessment. Mandatory tasks correspond to specific interactions such as loading a material, manipulating the structure, or activating certain visualisation features. Completion of these tasks is tracked automatically, and once all requirements are fulfilled, the evaluation quiz is unlocked. This conditional unlocking is represented in the diagram as the connection between the completion of scene-based tasks and the evaluation node. The session concludes when the learner finishes the quiz and the SCORM package reports completion to the LMS.

Despite their differences, both versions share the same core interaction principles: learners can examine crystallographic structures using intuitive controls, access defect visualisation tools, adjust display settings and progress through the activity at their own pace. The diagrams provide a clear illustration of how users can move between these functions without being constrained by a linear workflow, supporting a flexible and engaging learning experience.

5.1.5 Screenshots

The following screenshots illustrate the main functionalities of CuExplorer in both the AR and SCORM versions. They show representative stages of the user workflow, from material selection to the visualisation of crystal structures and crystallographic defects, as well as the integration of progress tracking in the SCORM module.

Table 1. Selection of screenshots from the CuExplorer application (AR and SCORM)

Screenshot	Description
 <p style="text-align: center;"><i>Figure 3. Plane detection in CuExplorer AR</i></p>	<p>This screenshot shows the initial plane detection stage, where the application identifies a suitable surface for placing the crystal models. Visual markers indicate that the AR plane has been successfully detected and is ready for interaction.</p>
 <p style="text-align: center;"><i>Figure 4. Crystal insertion and material identification in CuExplorer AR</i></p>	<p>A copper crystal structure has been placed on the detected surface. The material label and crystal system are displayed above the model, and the basic navigation UI (zoom and rotation) is visible.</p>

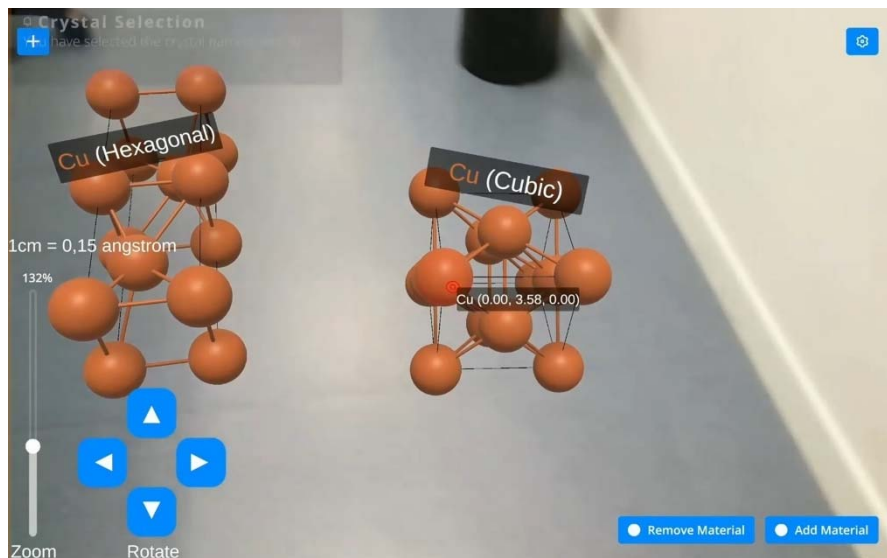


Figure 5. Multiple materials placed for comparison in CuExplorer AR

Two crystal structures (hexagonal and cubic forms of copper) are shown simultaneously in the AR scene. This feature allows learners to compare different crystal systems directly within the physical environment.

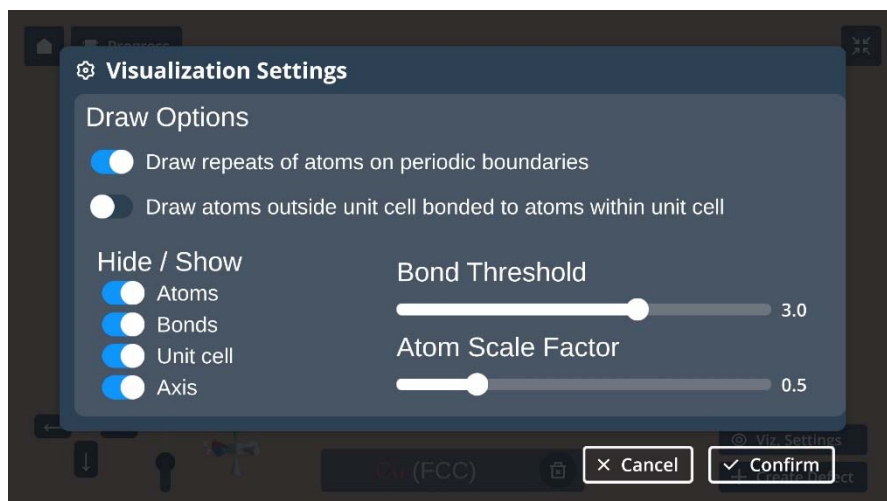


Figure 6. Visualisation settings panel in CuExplorer SCORM

The visualisation settings menu allows the user to adjust display options, including atom and bond visibility, unit cell representation, periodic repetition, and parameters such as atom scaling and bond threshold.

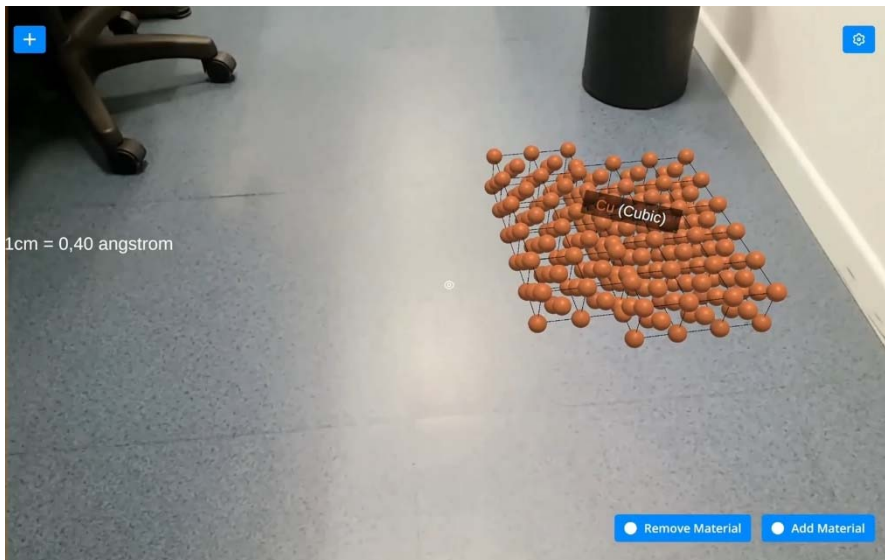


Figure 7. Extended crystal with screw dislocation applied

This screenshot presents a larger lattice structure containing a screw dislocation. The distortion produced by the dislocation is clearly visible, providing a realistic representation of a line defect that is difficult to convey in static images.

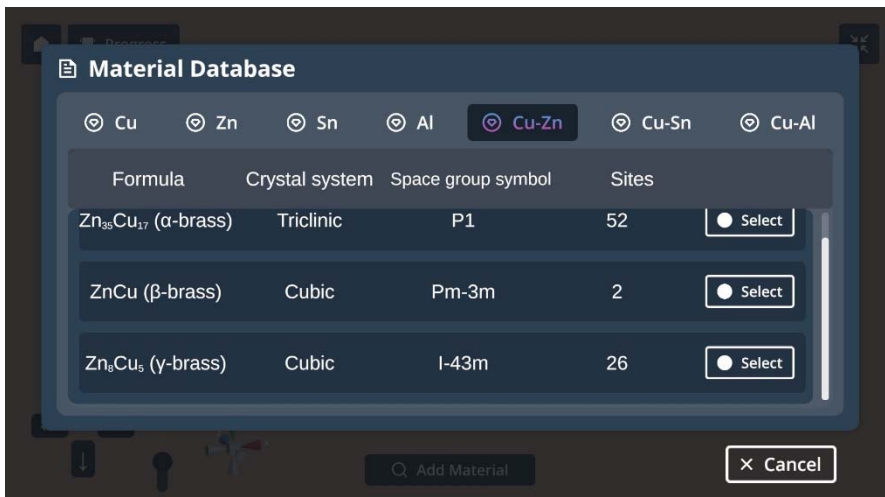


Figure 8. Material database panel in CuExplorer SCORM

This image shows the material selection interface within the SCORM WebGL version. Users can browse different material families, inspect crystal system information and choose a structure to load into the visualisation scene.

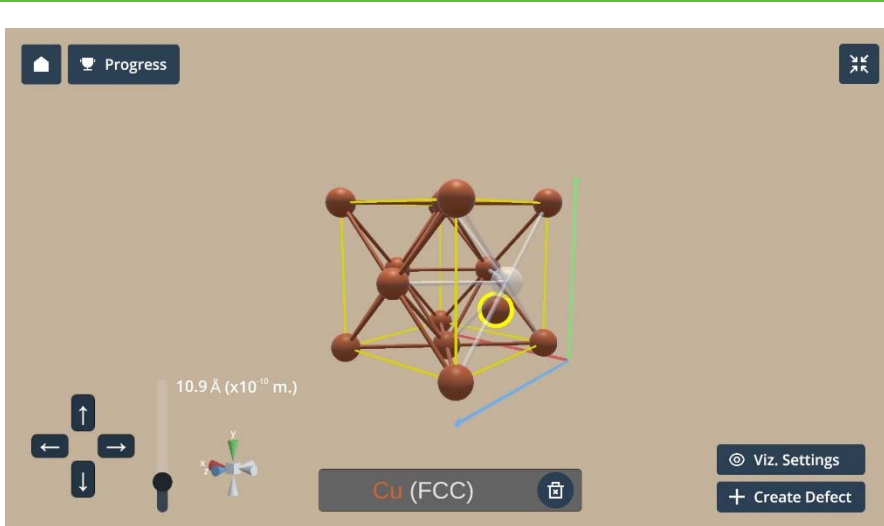


Figure 9. Crystal visualisation with point defects applied in CuExplorer SCORM

A copper FCC structure is displayed in the WebGL viewer with two active point defects (vacancy in transparent grey and self-interstitial highlighted in yellow). The navigation UI and access to the visualisation settings and defect creation tools are also visible.

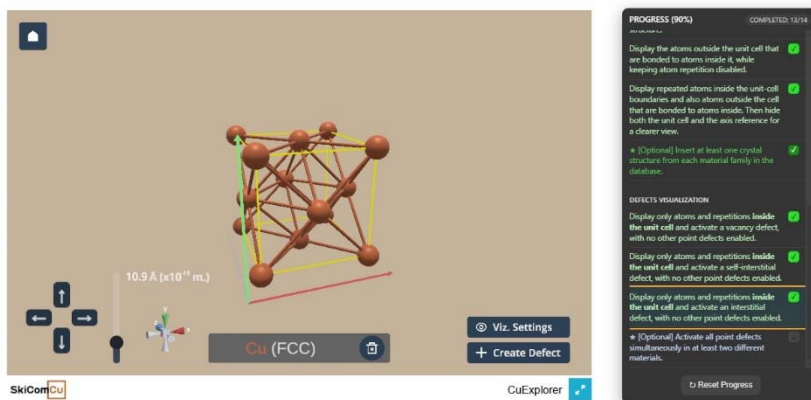


Figure 10. CuExplorer SCORM with task checklist running in LMS (LearningPoint)

This screenshot shows the progress and task checklist interface, which tracks mandatory and optional objectives within the SCORM package. Completed tasks are marked accordingly, and users can monitor their progress as they interact with the tool.

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5.2 Peirce-Smith Converter Inspector

5.2.1 Purpose and pedagogical role

The Peirce-Smith Converter Inspector has been developed to support the Copper Supply Chain module in WP3 by providing an interactive environment in which learners can explore the structure and operation of a Peirce-Smith converter. This furnace plays a central role in primary copper production, transforming copper matte into blister copper through a sequence of oxidation and reduction processes that can be difficult to understand when presented solely through text or static images.

The tool enables learners to interact with realistic 3D representations of the converter and to gain insight into both its physical components and the metallurgical processes occurring inside it. Through the Part Inspector mode, learners can examine each structural element of the converter, understand its function and recognise how the overall system is configured. The Operation Inspector mode complements this by illustrating the dynamic progression of the converting cycle, from charging of matte to the final removal of blister copper. The animations, internal cross-sections and information panels provide a clear representation of slag–matte separation, oxygen injection, chemical reactions and furnace behaviour.

By enabling learners to transition between structural exploration and process-based visualisation, the tool supports the pedagogical objective of linking equipment design to operational outcomes. This dual approach facilitates deeper conceptual understanding and promotes active learning, allowing trainees to observe how each operational stage contributes to the refining sequence. The tool therefore strengthens the learner's ability to interpret metallurgical workflows and reinforces the competences identified in WP2 as essential for workforce development in the copper sector.

5.2.2 Design approach

The Peirce-Smith Converter Inspector has been designed as a structured yet exploratory WebGL learning application that guides learners through the physical layout and operational stages of the converter. The design follows a dual-mode structure to support two complementary learning experiences: component-level inspection and process-level understanding.

In **Part Inspector mode**, the user interface highlights each accessible component as the cursor hovers over the 3D model. Selecting a part opens an information panel describing its name, function, and role in the converting process. This approach allows learners to progressively familiarise themselves with the converter's geometry, including tuyeres, refractory lining, matte and slag inlets, blowpipes, the rotating body and structural supports. The design emphasises clarity, spatial legibility and ease of navigation, enabling learners to focus on the functional purpose of each element without excessive visual complexity.

In **Operation Inspector mode**, the interface shifts to a process-oriented perspective in which learners can navigate through the sequence of eleven converting stages. A process selector at the bottom of the interface

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allows users to move forwards and backwards through each stage. For every stage, the application provides two complementary visualisations: an external animation illustrating furnace behaviour and an internal view showing material distribution, flow patterns and oxygen injection. These internal views help visualise matte-slag interaction, filling dynamics, oxidation reactions and blister copper formation. Process information windows are accessible at each stage to reinforce technical understanding.

The layout and transitions of both modes were designed to maintain consistency and minimise cognitive load. Navigation controls are placed in the lower left corner of the interface, while auxiliary panels such as information windows and interior views follow a consistent placement pattern to avoid confusing the learner. The tool's overall visual design prioritises interpretability, using simple shading, smooth animations and clear highlighting to ensure that learners can follow the progression of each task.

The dual-mode design allows the user to move between structural understanding and operational dynamics at any time, supporting a flexible exploration workflow that aligns with the modularity of the WP3 curriculum. This structure prepares learners to understand not only how the converter is built, but also how it behaves during the copper converting cycle.

5.2.3 Technical implementation

The Peirce-Smith Converter Inspector has been implemented as a Unity WebGL application using a modular architecture that supports both Part Inspector and Operation Inspector modes within a single project. As in the CuExplorer tool, the application is built with the Universal Render Pipeline (URP) to ensure consistent lighting, good performance and visual clarity across browser environments. Both modes rely on a shared 3D scene containing the converter model and interface elements, while mode-specific functions are activated through dedicated panels and interaction modules.

The converter model consists of optimised meshes suitable for real-time rendering. In the Part Inspector mode, interactive components use a highlight shader that activates when the mouse hovers over a selectable element. Each component is linked to a structured metadata file that contains its name, its function and contextual information. When the user selects a component, this metadata is displayed in an information panel. The interaction logic ensures that only one panel is active at a time to maintain clarity during exploration.

In the Operation Inspector mode, the tool uses a sequence of precomputed animations that represent the eleven stages of the converting process. These animations show the behaviour of matte, slag and injected oxygen as they evolve during the transformation into blister copper. A secondary camera generates the interior cross-sectional view, which is displayed in a dedicated panel. This arrangement allows the learner to observe both external and internal changes without altering the main view of the converter. The interface provides controls for switching views, accessing stage descriptions and moving freely through the process sequence.

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Navigation controls are consistent across both modes. Mouse-based orbiting, zooming and panning allow users to inspect the converter from any angle. On-screen buttons replicate these functions to support learners who may be less experienced with three-dimensional interfaces.

The tool is fully SCORM compatible. Communication with the SkiComCu learning platform is managed through SCORM plug-ins embedded in the WebGL template. These plug-ins record task progression, send the required information to the learning management system and control the unlocking of the evaluation quiz. Each interaction relevant to assessment, such as inspecting mandatory parts or completing key operational stages, is linked to a SCORM event to ensure accurate tracking. The WebGL template also manages responsive layout, fullscreen mode and the communication layer between Unity and the browser.

The internal structure of the application facilitates future extensions. Part Inspector and Operation Inspector functionalities are encapsulated within separate modules, which allows new animations, metadata or interactive elements to be added without affecting the shared scene or the core interaction components.

5.2.4 User interaction and functionalities

The interaction model of the Peirce-Smith Converter Inspector is structured around two complementary learning modes, Part Inspection Mode and Operation Inspection Mode, which can be accessed from the main menu. The overall interaction structure is shown in Figure 11. From the menu, learners can enter either mode, consult the tutorial or access the task checklist. The checklist records mandatory actions across both modes and enables the evaluation quiz once all required tasks have been completed.

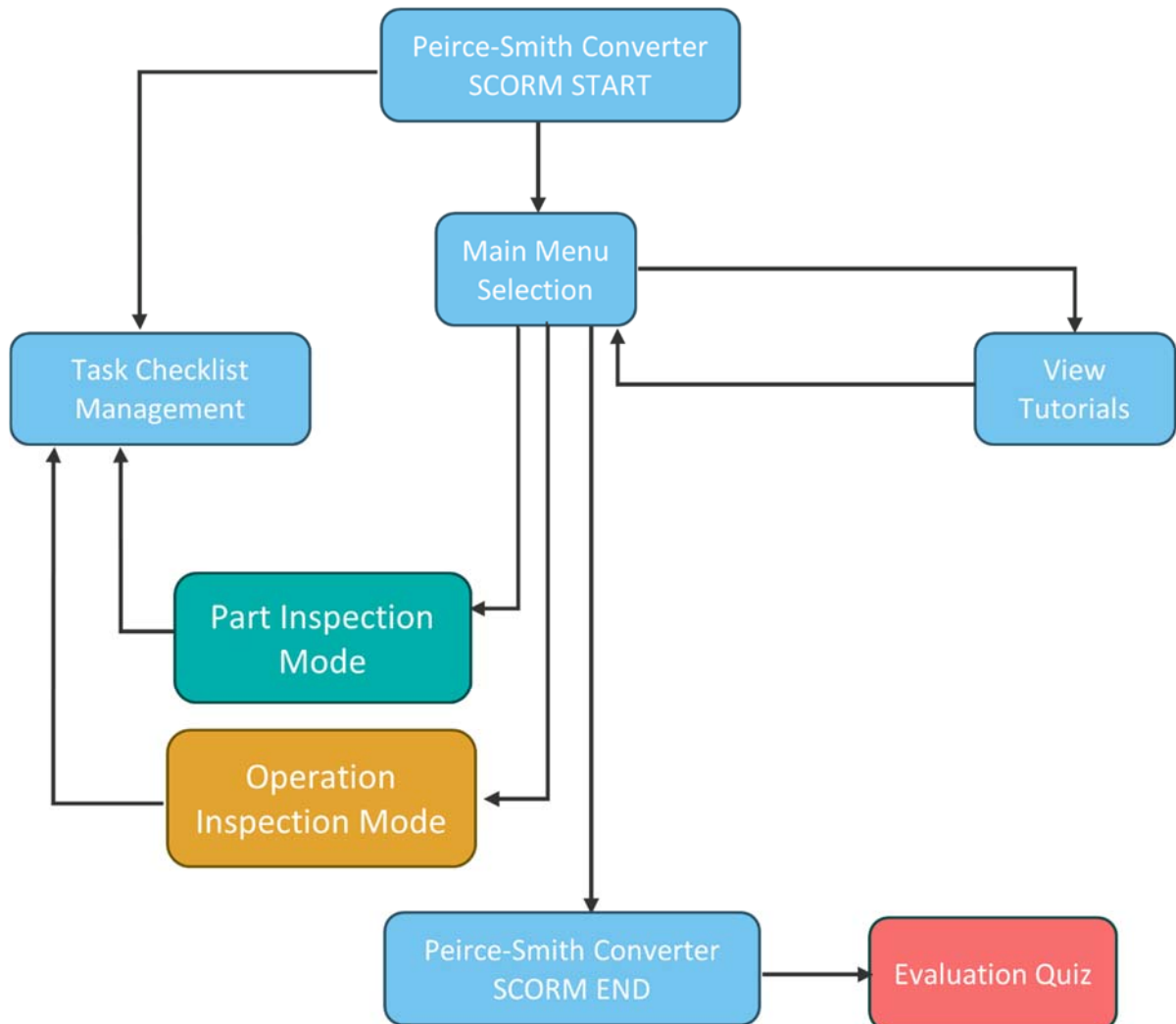


Figure 11. Peirce-Smith Converter general interaction flow

In Part Inspection Mode, learners focus on identifying and understanding the structural components of the converter. The interaction flow for this mode is shown in Figure 12. The central element is the 3D Converter View, which allows rotation, zooming and panning of the model. Learners can highlight components when hovering the cursor, select parts to display their description and navigate freely around the converter. Each part inspection contributes to the task checklist, and the learner may repeat interactions as needed. The mode allows open exploration, and users can return to the main menu at any time.

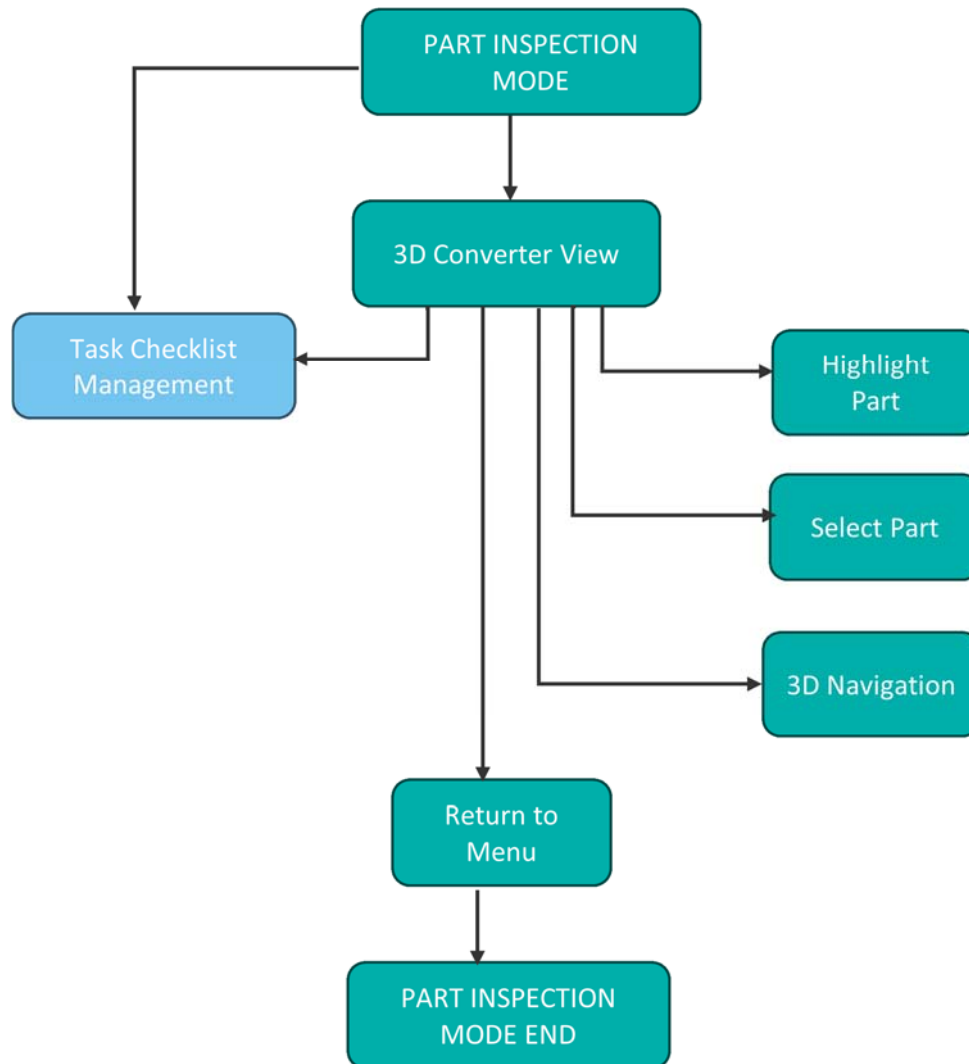


Figure 12. Part Inspection Mode interaction flow

Operation Inspection Mode provides a dynamic representation of the converting process. The interaction flow for this mode is presented in Figure 13. As in the Part Inspector, interaction begins in the 3D Converter View, where learners can navigate the model in three dimensions. From this view, users may access the animations that illustrate the evolution of matte, slag and oxygen injection across the converting stages, inspect the textual explanations associated with each stage and open the interior cross-sectional view to observe material transformations inside the converter. All these actions contribute to the task checklist, and each stage can be revisited freely. The mode can be exited at any moment through the return-to-menu command.

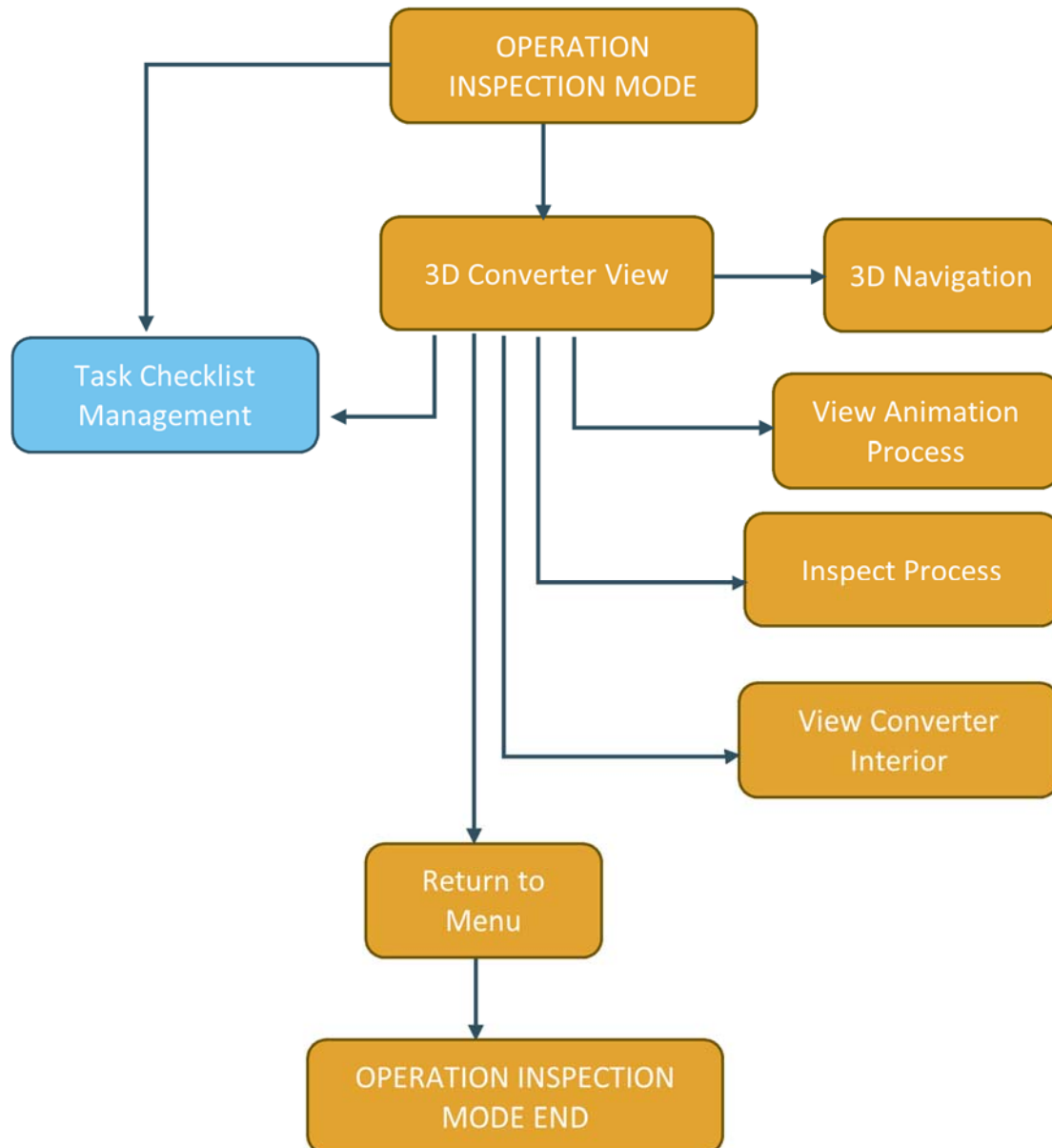


Figure 13. Operation Inspection Mode interaction flow

Both modes support flexible and non-linear exploration, allowing learners to progress according to their needs and preferred sequence of interactions. The task checklist remains active throughout the session and ensures that all required actions are tracked. Once the mandatory tasks have been completed in both modes, the evaluation quiz becomes available on the learning management system, marking the final step of the activity.

5.2.5 Screenshots

The following screenshots illustrate the main interfaces and functionalities of the Peirce-Smith Converter Inspector in both Part Inspection Mode and Operation Inspection Mode. These images provide an overview of how learners explore the converter's structure, access explanatory information and visualise the dynamic behaviour of materials during the converting process.

Table 2. Selection of screenshots from the Peirce-Smith Converter Inspector SCORM application

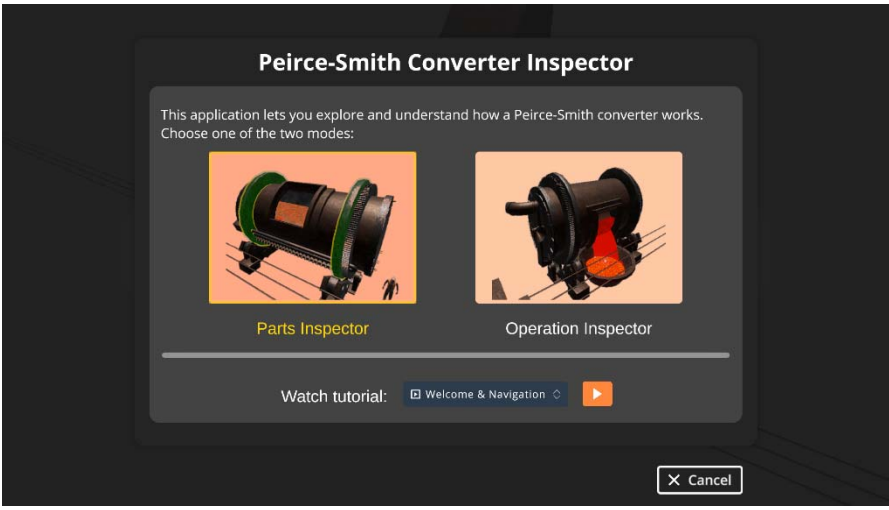
Screenshot	Description
	<p>This image shows the initial interface of the Peirce-Smith Converter Inspector, where learners choose between Part Inspection Mode and Operation Inspection Mode. A brief description introduces the purpose of the application, and tutorial links are also available.</p>

Figure 14. Main mode selection panel

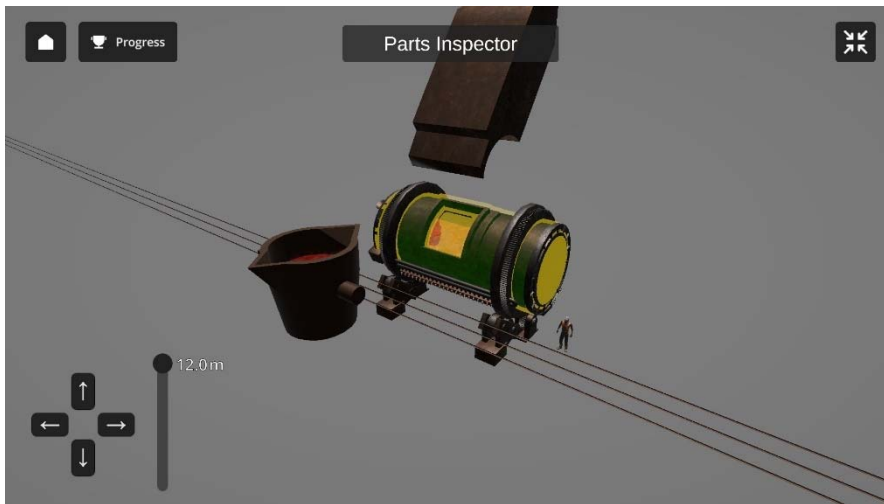


Figure 15. 3D Converter view in Part Inspector Mode

The screenshot illustrates the 3D Converter View used in Part Inspection Mode. Learners can freely orbit and zoom the model to observe the converter structure and its associated components. This view serves as the central workspace for inspecting each part.



Figure 16. Component description panel

This image shows the information panel that appears when a component, such as a tuyere, is selected. The panel provides a detailed explanation of the part's structure, function and relevance within the converting process. This supports conceptual understanding by linking physical equipment design to process behaviour

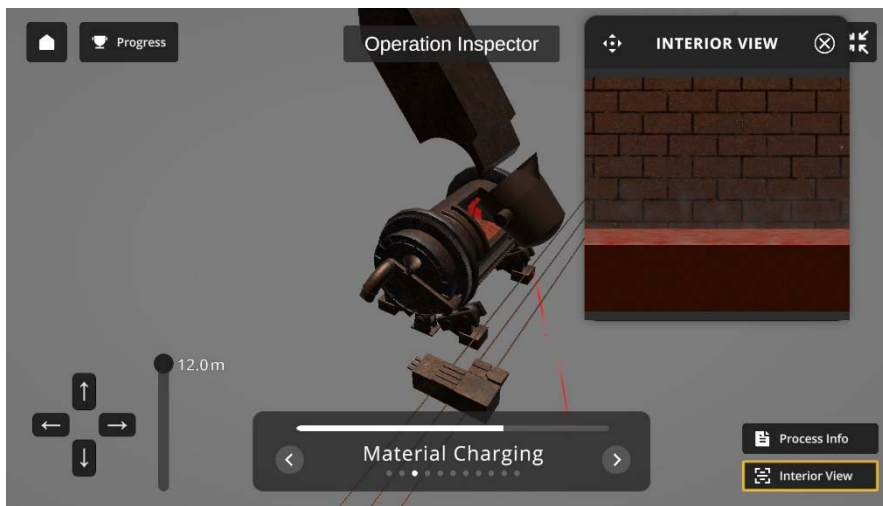


Figure 17. Animation and interior view in Operation Inspection Mode

The screenshot displays Operation Inspection Mode during a process stage. Learners can visualise the external animation of the converter and simultaneously access the interior cross-section view, which shows the behaviour of matte, slag and injected air inside the furnace. Navigation controls allow switching between stages of the converting cycle.

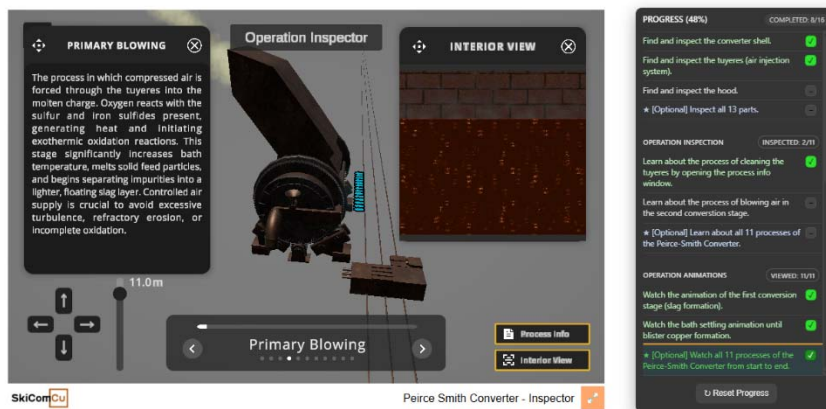


Figure 18. Process information and task management panel

This image shows the process information window, active during a converting stage, along with the task management panel on the right-hand side. The task checklist records mandatory and optional learning actions, allowing learners to track their progress through the module. Completion of required tasks contributes to unlocking the evaluation quiz.

5.3 Health and Safety Procedures in Mining (VR)

5.3.1 Purpose and pedagogical role

Health and Safety Procedures in Mining (VR) has been developed to support the Health & Safety module of WP3 by providing an immersive training environment in which trainees can practice safety procedures and operational behaviours in a mine without being exposed to real risks. Safety in mining relies mostly on situational awareness, compliance with protocols, and decision-making under adverse environmental conditions (low visibility, confined spaces, proximity to heavy machinery, or emergency situations). These aspects are difficult to internalize when they are presented solely through documentation, lecture-based training, or non-interactive audiovisual resources.

The application runs in virtual reality on Meta Quest devices and allows users to move through representative mining scenarios, interact with key elements (personal protective equipment, access control, safety and communication devices), and receive immediate feedback when unsafe practices are performed. The pedagogical objective is to transform regulatory and procedural knowledge into observable skills: correctly preparing equipment, maintaining safe distances, responding to environmental hazards, and executing appropriate actions in response to incidents.

The experience is structured as a set of six complementary scenarios that cover different stages of the operational workflow, from pre-entry preparation to the management of risk situations and emergencies. Through these scenarios, the simulator enables repeatable and standardized training, reinforces hazard identification, and supports the consolidation of operational routines. Overall, the tool contributes to the competencies identified in WP2 as critical for the sector, particularly with regard to safety culture, risk prevention, operational communication, and decision-making under pressure.

The scenarios directly support the learning outcomes of the Health & Safety module in WP3, particularly those related to hazard identification, safe behaviour near machinery, emergency response and procedural compliance in mining environments.

5.3.2 Design approach

The design of the VR application has been conceived as a guided training experience with active interaction, in which users learn through the execution of specific actions and immediate correction of risky behaviours. The application prioritizes clear objectives in each scene and consistency of interaction throughout the experience, so that the user's cognitive effort is focused on recognizing hazards and applying procedures, rather than on learning complex controls.

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The virtual environment recreates typical spaces of the mining context and organizes the training into progressive sequences. In an initial phase, users carry out preparation tasks (selection of clothing and personal protective equipment) and access procedures (validation via card at turnstiles), reinforcing the idea that safety begins before entering the operational area. Subsequently, users are confronted with scenarios involving movement through mine galleries, where spatial awareness and recognition of environmental risks are trained, including alerts when unsafe zones are entered (e.g., excessive proximity to walls associated with the risk of rockfalls) and situations in which an incorrect route decision requires the user to correct their choice and retrace their steps.

The design incorporates a high-risk scenario associated with the presence of heavy machinery in a low-visibility environment. In this situation, the experience emphasizes compliance with protocols and the correct use of a safety device (beacon) to stop a moving machine. The system validates the correct execution of the procedure (continuous circular movement) and penalizes unsafe behaviour through alerts and scenario restart in the event of a collision or loss of control of the device. This approach aims to consolidate safe behavioural habits near machinery, where anticipation and sustained attention are critical.

Finally, the simulator integrates an emergency scenario involving fire inside the mine, designed to train incident response. The user must activate the alert protocol using a telephone and communicate the situation to the responsible authority in order to initiate evacuation. In this way, the design not only trains prevention, but also coordinated response, communication, and the execution of procedures under stress.

5.3.3 Technical implementation

Health and Safety Procedures in Mining (VR) has been implemented in Unity as a virtual reality application for Meta Quest, using a modular approach that encapsulates each scenario as an independent functional unit. This architecture facilitates project maintenance and enables the incorporation of new scenarios or training variants without altering the core interaction logic.

Interaction is based on a natural VR model relying on locomotion and direct manipulation. Users can move through the environment and perform actions such as grabbing, pointing, and interacting with relevant objects (for example, personal protective equipment, access card, beacon, or telephone). Critical behaviours are implemented through action and state validation: proximity to hazardous zones, collision detection with machinery, verification of beacon movement patterns, and activation of communication events in emergency situations. The system also integrates controlled restart mechanisms in scenarios where training requires repeating the sequence after a failure, reinforcing learning through repetition and corrective feedback.

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The project incorporates performance considerations oriented to HMDs, prioritizing stable frame rates, optimization of geometry and lighting, and the use of visual and interaction resources appropriate for an immersive environment. Regarding the development status, the structure supports planning iterations, incorporating usability improvements, feedback adjustments, refinement of procedure validation, and content expansion in line with the needs of the WP3 module.

Unlike the WebGL-based XR tools, the VR application is not delivered as a SCORM object but as a standalone immersive experience designed for HMD devices, complementing the SkiComCu platform through instructor-led or supervised training sessions.

5.3.4 User interaction and functionalities

The interaction model of the Health and Safety Procedures in Mining VR application is structured as a guided experiential workflow, designed to simulate realistic safety scenarios while maintaining clear control over learner actions and progress. The overall interaction flow is summarised in Figure 19, which illustrates the sequence of preparation, task execution, feedback and session completion.

The experience begins with an initial preparation phase, where the learner is introduced to the training objectives and the basic interaction controls within the virtual environment. From this point, the user enters the mining scenario and is required to move through the environment using natural VR locomotion and interaction techniques. Navigation and object interaction are performed through standard VR mechanisms such as teleportation, pointing and grabbing, ensuring intuitive control and minimising cognitive load.

As shown in Figure 19, the core of the interaction is task driven. Learners are presented with specific safety-related objectives, such as identifying hazards, selecting appropriate protective equipment or performing correct operational procedures near mining machinery. Each task requires explicit user actions and is validated by the system before progression is allowed. Incorrect actions or unsafe behaviour trigger immediate feedback, including visual cues and instructional messages, reinforcing correct practices.

The workflow includes conditional branching based on user performance. If a task is completed correctly, the learner progresses to the next stage of the scenario. If errors occur, the system provides corrective feedback and may require the task to be repeated before continuation. This loop, ensures active engagement and supports learning through trial, error and reinforcement.

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The interaction model also incorporates emergency and risk scenarios, where the learner must react under time pressure or unexpected conditions. These situations are designed to enhance situational awareness and decision-making skills in a safe, controlled environment. Progress through the scenario is continuously monitored, and completion of all required tasks leads to the finalisation of the session.

The application provides security-oriented functionalities, including hazard identification through contextual signals and alerts, training in basic procedures (equipment use, controlled access, and operation of safety devices), and the execution of incident response actions (emergency communication and evacuation activation). Feedback is delivered immediately through visual and auditory elements, reinforcing the link between action and consequence. In risk scenarios, the system incorporates penalties and flow resets when safety conditions are not met, helping to consolidate correct behaviours and to internalize the importance of adhering to protocols in real-world situations.

At the end of the experience, the learner exits the virtual environment and receives a summary of completed actions. This structured interaction flow ensures that all critical safety procedures are practiced while allowing sufficient freedom of movement and interaction to maintain realism. The explicit mapping between user actions and system validation, as illustrated in Figure 19, supports consistent training outcomes and repeatable assessment of learner performance.

Overall, the interaction maintains a balance between guidance and exploration: the user has the freedom to move and act within the environment, while the system verifies essential steps and emphasizes safe decision-making, in alignment with the training objectives of the Health & Safety module.

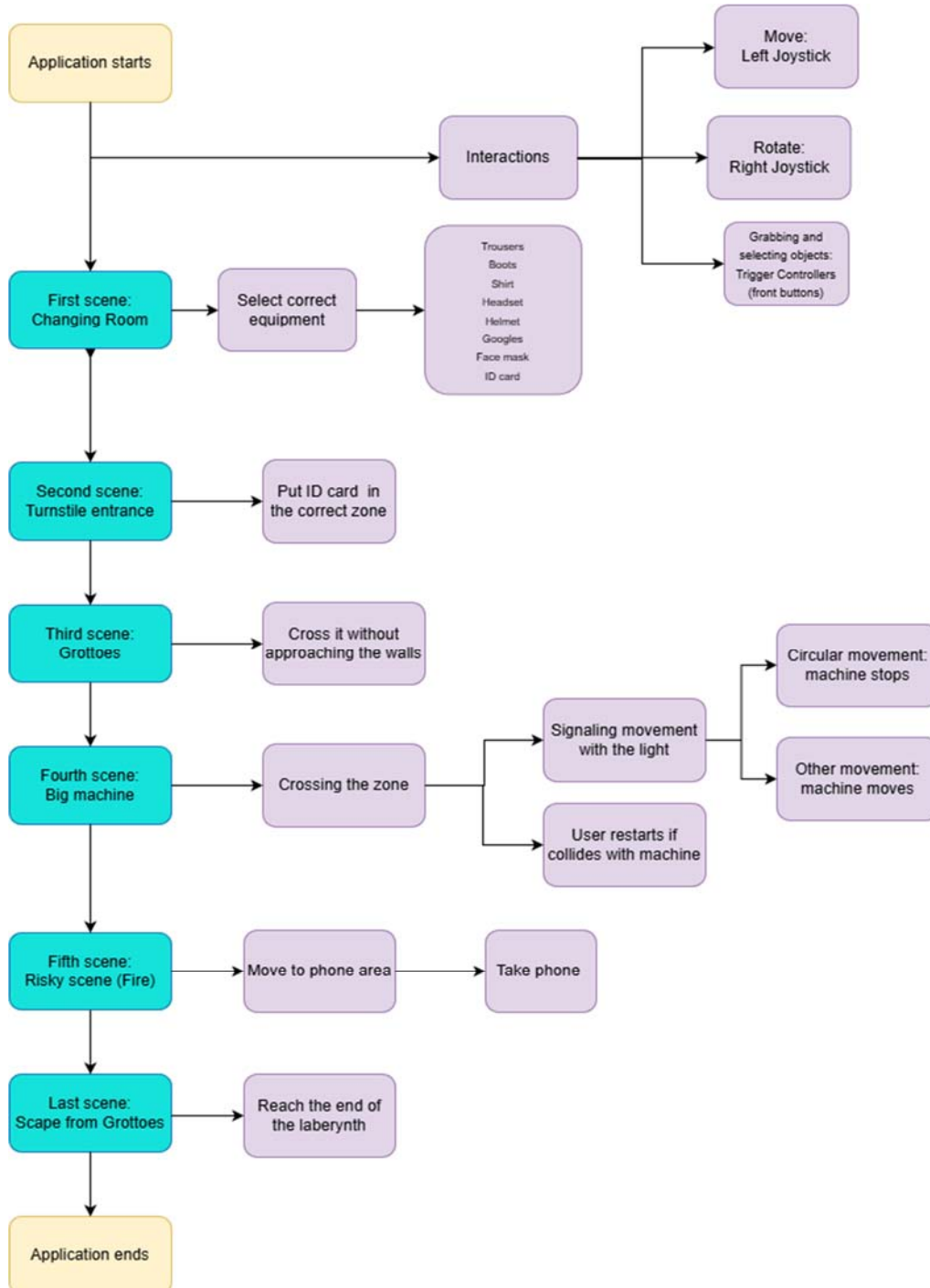


Figure 19. VR application general interaction flow

5.3.5 Screenshots



Figure 20. Changing room scenario

The screenshot shows the first scene of the application. The target of this area is to get the necessary equipment to go into the mine.



Figure 21. User avatar in changing room scenario

It shows the user's avatar with all the elements added before going to the mine.



Figure 22. Equipment to move through the mine

These are all the elements needed to go through the mine in a safe way.

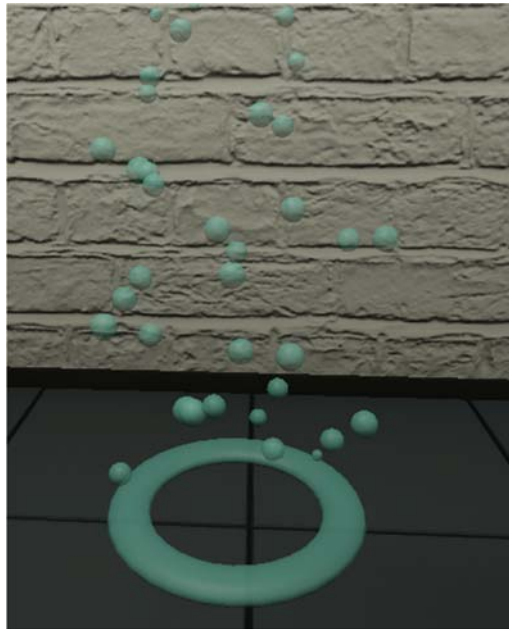


Figure 23. Checkpoint teleporter object

This object is used to teleport to the next scene. It will be found in each scene.



Figure 24. Turnstile entrance.

The user must take the ID card and cross to the other side of the turnstiles.



Figure 25. Grotto scenario

This scene shows the user inside the grotto, where it must move to the end, without approaching the walls



Figure 26. Big machine

In this environment, the user needs to cross the area without been touched by the machine. It is necessary to move the hand light correctly.



Figure 27. Hand light and instructions in the big machine scene

The image shows the hand light to signal the movement as well as the warning panel giving instructions.



Figure 28. Fire scene

In the image there are a few explosions alerting the user that is a risky area.



Figure 29. Phone to call alerting to danger

The phone is used to advise about the danger in the environment.

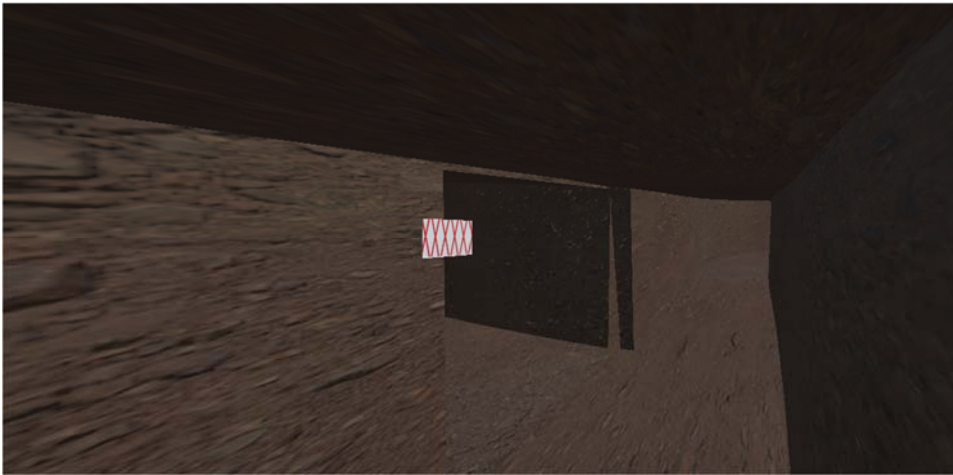


Figure 30. Final grotto to exit the mine

The user must choose between different ways. In case it takes the wrong one, it must return back to continue. The red marks indicate the wrong way.

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Conclusions

This deliverable presents the first development of the SkiComCu XR learning tools, which constitute an essential component of the project's strategy to enhance digital learning and improve the effectiveness of the modular curriculum developed in WP3. The three applications introduced in this phase demonstrate the significant potential of immersive and interactive technologies to support knowledge acquisition in areas such as physical metallurgy, copper processing and health and safety procedures.

The XR tools were designed and implemented to complement the outcomes of WP2 and WP3 and to align with the technical framework established in D4.1. The applications provide learners with visual, interactive and experiential resources that help bridge the gap between theoretical content and practical understanding. CuExplorer facilitates the exploration of crystal structures and material defects, the Peirce-Smith Converter Inspector illustrates key process stages within the copper value chain and the VR training environment introduces realistic scenarios for practising safety-related decision-making.

From a technological perspective, the use of Unity, WebGL, AR Foundation, ARCore and the XR Interaction Toolkit ensures that the tools are scalable, maintainable and compatible with the learning platform. Their deployment through SCORM packages or VR devices supports flexible integration into the training pathways of the SkiComCu digital ecosystem. These tools form a coherent and expandable foundation for XR-based learning within the project.

While two of the tools are fully operational at this stage, the VR safety training module remains under development and will be completed by month 30. This phased approach ensures that each application meets the project's pedagogical and technical requirements and allows further refinement based on user feedback and platform integration processes.

At the time of this deliverable (M18), the VR application provides a functional and fully navigable training experience covering the main safety scenarios. Further refinements, usability improvements and content extensions will be implemented up to month 30, including scenario tuning, feedback optimisation and additional validation mechanisms.

In summary, this first development stage establishes a solid basis for the use of XR technologies in SkiComCu. The tools delivered enhance learner engagement, improve conceptual clarity and contribute to the project's long-term goals of supporting workforce development, digital transformation and innovation within the raw materials sector.

Glossary of Acronyms

Acronym	Meaning
AR	Augmented Reality
ARCore	Google framework for augmented reality on Android devices
AR Foundation	Unity framework for building cross-platform AR applications
EIT	European Institute of Innovation and Technology
HMD	Head Mounted Display
ILT	Instructor-Led Training
KPI	Key Performance Indicator
KIC	Knowledge and Innovation Community
LMS	Learning Management System
SCORM	Sharable Content Object Reference Model
SQF-Cu	Sectoral Qualifications Framework – Copper
UI	User Interface
UPM	Universidad Politécnica de Madrid
VR	Virtual Reality
WebGL	Web Graphics Library for rendering interactive 3D content in web browsers
WP	Work Package
xAPI	Experience API (also known as Tin Can API)
XR	Extended Reality
XRI	XR Interaction Toolkit (Unity framework for VR interaction)