Analysis of needs and requirements for an on-cloud collaborative environment to support conservation workflows

Deliverable n. 2.2

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COLOURS Consortium

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Executive Summary

This deliverable presents the analysis and prioritisation of needs and requirements for an on-cloud collaborative environment supporting conservation-restoration workflows (Task 2.4). It complements D2.1, which addresses the COLOURS digital tools, and focuses on collaboration and on COLOURS Scenario 1. The analysis draws on the Ljubljana workshop and survey, two online co-design workshops on internal pilots, the workflows described by the conservator-restorer partners, and the ECHOES community consultation.

Today, information on an intervention is exchanged mainly through separate documents in heterogeneous formats, so it is often lost or scattered. The analysis of eight decisional stages shows that only key decisions require real-time interaction, while preparation, documentation and review can take place asynchronously. The Collaborative Simulation Environment (CSE) should therefore act as a persistent shared decision space connecting the two modes. On this basis, the deliverable defines several requirements for the CSE, each traced to its source and given an indicative priority, and clarifies the position of the CSE within the ECCCH. Final priorities will be set after the feasibility assessment in the internal pilots and reported in the second iteration at M24.

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List of Abbreviations

AR – Augmented Reality
CSE - Collaborative Simulation Environment
CVE - Collaborative Virtual Environment
C-R – Conservation - Restoration
HCSE – See CSE
ECCCH – European Collaborative Cloud for Cultural Heritage
ECHOES – European Cloud for Heritage OpEn Science
EOSC – European Open Science Cloud
3DGS – 3D Gaussian Splatting
HDT – Heritage Digital Twin
HMD – Head-mounted display
HSI - Hyperspectral Imaging
EU – European Union
CKR – Colour Knowledge Repository
GA – Grant Agreement
ISPC – Istituto di Scienze del Patrimonio Culturale (Institute of Heritage Science)
MoSCoW - Must have, Should have, Could have, Won't have (prioritisation scheme)
MuLaX - Multi-Layer eXtensible eXplorer
MR – Mixed Reality
OCRA - Online Conservation-Restoration Annotator
RTI - Reflectance Transformation Imaging
PACT – People, Activity, Context, Technology (design methodology)
VR – Virtual Reality
WP – Work Package
XR - Extended Reality
XRF - X-ray Fluorescence

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1. Introduction

Conservation activities are characterized by multidisciplinary and iterative workflows in which information is generated, interpreted, and refined through the interaction of conservators, conservation scientists, curators, heritage managers, and digital specialists. The resulting decision-making process is typically non-linear, relying on the continuous integration of analytical data, condition assessments, documentation records, and expert knowledge to define and validate appropriate conservation actions.

In this context, collaborative environments represent virtual spaces designed to facilitate the sharing, management, interpretation, and exploitation of conservation-related information. By integrating data, workflows, and expert knowledge within a common cloud-based infrastructure, a collaborative environment can support evidence-based decision-making and improve communication among stakeholders throughout the conservation workflow.
The objective of this deliverable is to analyse user needs, identify the main decisional stages of conservation workflows, and define the functional and technical requirements that should guide the development of a cloud-based collaborative environment dedicated to heritage conservation.

Within COLOURS, the *Collaborative Simulation Environment* (CSE, or HCSE) – mainly designed and built in WP4 – represents a simulation environment allowing restorers, conservators and professionals to operate across multiple digital spaces, offering advanced features for collaboration, semantic enrichment and interconnection with COLOURS tools, to boost decision-making processes.

This deliverable serves to identify, highlight and analyse emerging user needs and requirements able to shape CSE components.

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2. Background

Collaborative Decision-Making processes [Wilson 2003, Tisdall 2013] enable contexts where is possible to involve community members and share knowledge about the decisions to be made and agreements on decision-making principles to activate. Collaborative decision-making processes succeed in resolving conflicts, uncertainties, ambiguities related to specific community-driven processes or workflows, combining valuable contributions of all participants involved in each decision [Cerreta et al. 2020].

Recent advancements in Web3D technologies allow to build rich, open and interactive social spaces where collaborative decision-making processes can take place. Thanks to Web3D technologies, such virtual spaces are virtually accessible everywhere, through standard web browsers. Literature and recent surveys mainly involve two collaboration models: synchronous and asynchronous [Yu et al. 2016, Schäfer et al. 2022, Huh et al. 2019]. *Synchronous collaboration* represents live, real-time interaction requiring each participant to be available at the same time. *Asynchronous collaboration* allows participants to work together on their own schedules and paces, without being present at the same time.

There are existing Web3D platforms (proprietary solutions, or solutions operating in different fields, with different target users) also analysed in COLOURS *Scenario 1* ("Collaborative Decision-Making for Museum Artifact Restoration") - that may offer a few inspirations for the realization of CSE in COLOURS.
LearnBrite[1] for instance is a web-based ecosystem specifically geared toward corporate learning and training. It is the preferred choice for converting traditional educational materials (PDFs, static videos) into interactive virtual classrooms.
Spatial.io[2] is an online platform to create, share and explore virtual 3D worlds, multi-user learning experiences and classrooms. It is accessible via web browser on mobile or using head-mounted displays (HMDs).

[1] https://learnbrite.com/
[2] https://www.spatial.io/

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Arrival.Space[3] is a 3D social platform focused on capturing reality and sharing next-generation content, through native integration of 3DGS (3D Gaussian Splats). It offers "Hub Spaces" (pre-configured environments with connection portals/gates) and "Empty Spaces" (blank canvases).

Within the context of COLOURS project, the open-source ATON framework [Fanini et al. 2021, Fanini et al. 2025] by CNR ISPC, allows to build web-applications involving both synchronous and asynchronous collaboration models[4]. Web applications built on top of ATON are accessible with every device (from mobile up to XR devices) and offer support for multiple formats (including multi-resolution 2D/3D data, point-clouds and 3DGS) – see D3.1.



Figure 1: Sample collaborative Web3D applications built on top of ATON framework

The framework was already employed in previous Cultural Heritage projects to realize collaborative virtual environments (see Fig. 1) for shared and interconnected discussion spaces in Architecture field[5], collaborative Immersive Analytics [Fanini, Gosti 2024], collaborative design of museum exhibitions [Massidda et al. 2025] and collaborative guided experiences [Pescarin et al. 2023].

To describe requirements that will define the components of the Collaborative Simulation Environment (CSE) in COLOURS WP4, next sections will focus on analysis of user needs and emerging key decisions in conservation-restoration processes.

[3] https://arrival.space/welcome
[4] https://osiris.itabc.cnr.it/aton/ and https://aton.ispc.cnr.it/
[5] https://metamic.it/

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The CSE within the ECCCH ecosystem

The European Collaborative Cloud for Cultural Heritage (ECCCH), built by the ECHOES project, offers shared services to sister projects. These include federated authentication, the Knowledge Base and the Heritage Digital Twin Ontology. Applications are deployed in its Application Layer as Vertical Applications (ECHOES D8.1). COLOURS is integrated as a single Vertical Application, of which the CSE is one component; its results reach the ECCCH through the CKR (D7.1).

Within ECHOES, CNR-ISTI is developing OCRA (Online Conservation-Restoration Annotator), a Vertical Application for the collaborative documentation and semantic annotation of 3D models, 2D images and RTI, with team roles, controlled vocabularies and report generation[6].

OCRA and the CSE share some functions, notably spatial annotation and reporting, but their focus differs. OCRA addresses the structured documentation of an object. The CSE addresses collaborative decision-making on interventions: comparing alternative scenarios and simulation results, synchronous and asynchronous sessions, immersive evaluation, and decision records. The CSE will therefore keep its annotation and reporting functions focused on decision support. Data exchange between the two applications will be possibly assessed with the OCRA developers, considering that OCRA is still under active development.

[6] https://www.echoes-eccch.eu/ocra/

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3. Analysis

3.1 Methodology and evidence base

D2.2 and D2.1 draw on the same stakeholder engagement process carried out in WP2 (T2.1–T2.4) during the first project year. The two deliverables split the COLOURS scenarios between them. D2.1 addresses the needs and requirements for digital tools (Scenarios 2, 3 and 4). D2.2 addresses the collaborative dimension of conservation-restoration work, the collaborative decision-making environment (Scenario 1). "Definition of requirements for on-cloud collaborative environments" is one of the pillars of the joint WP2 analysis (D2.1, §3.1). This section summarises the sources used and extracts the evidence that is specific to the collaborative environment, so that each requirement in Section 5 can be traced to its origin.

Sources. The analysis is based on four groups of sources.

1. **Workflow templates**. Conservator-restorer partners completed a structured template for each case study, describing phases, decision points and operational steps. These templates produced the shared conservation-restoration workflow (D2.1, §3.2), which underlies the decisional stages in Section 4.
2. **Ljubljana workshop (12 May 2026)**. The COLOURS-ECCCH workshop "Shaping the Future of Digital Practices in Conservation-Restoration" was held at the Archives of the Republic of Slovenia. COLOURS tools were demonstrated to conservator-restorers, and feedback was then collected through a survey.
3. **Online co-design workshops on two internal pilots**. The first addressed Pilot 2a,b, the wooden polychrome sculptures by J. A. Eglauer (Bratislava City Gallery). The second addressed Pilot 1a, the Baroque painting Adoration of the Holy Cross (Ljubljana). The workshops brought together conservator-restorers, heritage researchers, curators, tool experts and digital heritage specialists. Each one combined plenary polling on use cases, users, goals and design constraints with breakout sessions. In these sessions, interdisciplinary groups built storyboards of end-to-end workflows using an adapted version of the CoDesign Tool developed in the PERCEIVE project. The workshop methodology foresaw a MUST / SHOULD / COULD / WON'T classification of requirements (D2.1, Annex 2).

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4. **ECHOES community consultation.** The ECHOES consultation on the needs of Cultural Heritage communities (ECHOES D4.1) provides a European-level reference on the digital practices of conservation-restoration professionals.

The design of the Collaborative Simulation Environment in WP4 has also been discussed within the consortium. This discussion is treated as design input, not as user evidence. Where a requirement originates from design considerations rather than from stakeholder input, this is stated explicitly in Section 5.
Evidence relevant to the collaborative environment. Table 1 lists the findings from these sources that concern collaboration, shared decision-making and documentation. Each finding has a code (E1–E11), which the requirements table in Section 5 uses as its source reference.

Table 1: evidence from sources

E1	Collaboration among scientists, curators and other stakeholders is one of the main intended uses of the COLOURS tools, and it was indicated as an integration area for several of them.	Ljubljana survey (D2.1, Annex 2a)
E2	Automatic generation of condition reports, including a PDF report produced at the end of a working session, is among the recurring features requested.	Ljubljana survey
E3	Users need to display several analytical results for the same spot of an object at the same time, with better integration between datasets.	Ljubljana survey
E4	The complexity of the required input data, and its mismatch with the data normally acquired in practice, is the main barrier to adoption (78% of respondents).	Ljubljana survey
E5	A "hybrid remote expert commission" was developed as a use case: distributed experts jointly evaluate cleaning, overpaint and format interventions on a shared digital twin, with diagnostic evidence and predictive simulations.	Co-design workshop, Pilot 1a

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E6	Required functions: invitation of remote experts with permissions and session management; meeting-output packages, decision logs and audit trails; traceability from evidence to decision; region-based confidence and uncertainty tagging.	Co-design workshop, Pilot 1a
E7	Required functions: comparison of alternative hypotheses (A/B/C), version management, collaborative decision logging, exportable comparison packages.	Co-design workshop, Pilots 2a,b
E8	Both workshops linked COLOURS tools into end-to-end workflows rather than using them separately. In the Pilot 1a workshop the common workflow was evidence retrieval → diagnostic mapping → scenario creation → simulation → collaborative review → decision capture → optional public communication. In the Pilots 2a,b workshop it ran from the CKR, through MuLaX/ATON and variant management, to collaborative decision-making and public presentation. Across both, three functional layers emerged: evidence, decision and communication.	Co-design workshops, Pilots 1a and 2a,b (D2.1, Annex 2b)
E9	Adoption of advanced digital methods is still limited: about 35% of respondents use 3D modelling and visualisation tools, and about 23% use formal knowledge representation tools.	ECHOES consultation (D2.1, §1.3)
E10	The sector is cautious about cloud infrastructures, because of concerns about data ownership, privacy, intellectual property and long-term digital preservation.	WP2 stakeholder engagement (D2.1, §3)
E11	Information on an intervention is exchanged between professionals and institutions mainly through condition reports. Each institution tends to use its own format, so information is often lost when reports are passed on or reused. Partners request the automatic production of condition reports from the data stored in the COLOURS tools.	Ljubljana workshop; consortium meetings

From evidence to requirements.

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The analysis follows the approach adopted in D2.1. Findings are first expressed as stakeholder needs, meaning problems, constraints or expected forms of support. They are then related to the decisional stages of the conservation-restoration workflow (Section 4). Finally, they are translated into functional requirements. Priorities are discussed in Section 5.

Limitations. The evidence base has three main limitations.

Small sample. The survey sample is small and drawn mainly from the community reached through the project network.

Two object types only. The co-design workshops covered two pilots, a polychrome sculpture and an easel painting. Film, photographic and archaeological case studies are therefore not yet directly represented.

The description of current documentation practice (Section 3.2) is based on input from the end-user partners at the Ljubljana workshop and in consortium meetings; a more systematic analysis of the tools in use will be carried out in the second iteration

These limitations will be addressed in the second iteration of this deliverable at M24. That iteration will follow the feasibility study performed on the basis of the diagnostic data available on the internal pilots, extend the evidence with the results of the internal pilots and of the validation of the collaborative environment (T12.4).

3.2 User Needs

Among the broader needs of conservator-restorers, D2.1 highlights the importance of recording the condition and treatment history of an object in a way that is objective and can be reproduced. Records of this kind inform decisions within the team and allow the work to be accounted for to those who fund, own or oversee it (D2.1, Chapter 4). Across the tools assessed in D2.1, stakeholders also asked for documentation and reporting to be less manual (D2.1, §4.1). In the Ljubljana survey, the automatic generation of condition reports was one of the improvements requested most often (E2).

This deliverable looks at the same issue from the angle of collaboration, complementing the data-flow analysis foreseen in D2.1 (§3.1). At the Ljubljana workshop and in consortium meetings, the end-user partners explained that professionals and institutions working on an intervention share information mostly

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by exchanging separate documents, the condition report being the main one. EN 16095:2012 sets out the minimum information that a condition report should contain, but leaves its structure to individual organisation, explicitly acknowledging the coexistence of multiple reporting formats. Consequently, institutions often rely on their own template, and part of the information gets lost when a report changes hands or is reused for a later intervention (E11). At the same time, analytical results are frequently maintained on separate datasets that are hard to consult side by side (E3).

Research projects that experimented with shared digital documentation for restoration show both the benefits of a common record and the persistence of these difficulties. In the restoration of the Neptune Fountain in Bologna, for example, a web-based system that linked the documentation of a team of more than forty experts to a 3D model of the monument proved effective in practice. Its authors noted, however, that agreed procedures for archiving and retrieving restoration data were still lacking [Apollonio et al. 2018]. Digital documentation also raises the question of long-term access. More than twenty years ago, Moore [2001] identified the preservation of future access to digitised conservation records as the main drawback of digitisation, given the pace of technological change. The sector still regards this as a concern (D2.1, Chapter 3).

Together with the CKR and MuLaX, the collaborative simulation environment addresses part of this gap. The CKR stores and versions the shared record, MuLaX links analytical data to the 3D model of the object and will generate condition reports from it, and the CSE allows professionals to annotate, discuss and decide on the same record during and between sessions. This is reflected in requirements COL-CE-03 (Spatial Annotations), COL-CE-06 (Reporting) and COL-CE-20 (Controlled Vocabularies).

Close collaboration in WP2, in collecting and analysing the individual user needs addressed by the COLOURS tools revealed that the specific needs of experts depend on their role and the activities in which they are involved, according to their area of expertise within the multidisciplinary ecosystem surrounding heritage assets. However, as conservation-restoration decisions inherently rely on consensus, data exchange, and cross-disciplinary interpretation, the specifications of the tools cannot focus solely on the utilities of individual users. Instead, our design framework of the Collaborative Simulation Environment (CSE) prioritises collaborative functionalities, such as shared annotation layers, synchronous review spaces and role-based data permissions, that bridge divergent working cultures and practices as well as institutional protocols.

Therefore, the development of the CSE requires us to look beyond individual tasks to the collaborative network of actions that form part of a heritage object conservation project. Our user mapping reflects the community of practice, which includes conservators, scientists, curators and site managers. These individuals

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must work together, jointly interpret findings and negotiate interventions. Consequently, the CSE must balance specialised individual analytical/practical needs with collective decision-making environments, shared workspaces and auditable consensus-building tools.

In this framework, some specific needs and challenges have been identified

i. **Expertise/role-based needs**

- **Core practitioners/C-R specialists** need rapid, low-friction field capture, intuitive visual interfaces and offline-to-online synchronisation on mobile hardware. **Heritage scientists** require raw data ingestion, spectral/chemical dataset handling, metadata preservation, and integration with analytical standards (e.g., HIS, XRF mappings, microscopic and spectroscopic point analysis).
- **Curators and art historians** prioritise contextual provenance, condition history narratives, terminology alignment (thesauri/ontologies like CIDOC-CRM), and non-technical summary visualisations.
- **Collection managers, site directors** focus on risk management, regulatory compliance, intervention sign-offs, and long-term preventive monitoring.

ii. **Divergent digital maturity & access constraints**

- **Varying technical baselines**: In contrast to well-resourced national institutes or university labs, private-practice conservators and small regional museums frequently lack dedicated IT infrastructure. Tools must therefore avoid high-spec hardware dependencies or overly steep learning curves.
- **Connectivity barriers**: Fieldwork often has poor or no internet connectivity. A collaborative platform must therefore account for asynchronous work, local offline caching and conflict resolution mechanisms when synchronizing with the cloud. Offline work is not addressed in this iteration and it will be reassessed at M24

iii. Different academic disciplines or professional cultures communication challenges and consensus-building mechanisms

Different specialists describe the same object using radically different vocabulary and evidence bases. Tools must facilitate discipline bridging and knowledge integration, unifying qualitative observational notes and quantitative instrumental measurements within a common framework referenced to the digital representation of the object.

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iv. Data Governance, Ethics, and Attribution

Collaboration involves sensitive issues: proprietary diagnostic techniques, embargoed research data, museum security documentation, and copyrights over high-resolution imaging data.

Tools must incorporate granular **access control and intellectual credit**, ensuring that sharing preliminary data does not compromise provenance, confidentiality, or authorial attribution before formal publication.

3.3 Restoration-Conservation workflow

Conservation activities can be described as a sequence of interconnected phases involving data acquisition, interpretation, planning, intervention, and documentation. Although workflows vary depending on the type of heritage asset and institutional context, common operational stages can be identified. Within the scope of WP2, during the analysis of Stakeholder engagement and requirements, a common, broadly shared and essentially linear workflow was developed, providing a common reference framework through which recurring stages, needs, and opportunities for digital support can be identified across different contexts.

The workflow typically begins with the collection of existing documentation and a preliminary assessment of the object. Scientific investigations and diagnostic analyses provide additional evidence regarding materials, techniques, degradation processes, and previous interventions. The resulting information is then interpreted collaboratively to support conservation planning and intervention strategies. Finally, all actions and outcomes are documented and archived to ensure future accessibility and knowledge preservation (see D2.1, §3.1 General needs, §3.2 The digital dimension of a conservation-restoration workflow).

3.4 Collaborative Decision-Making environment for Museum Artifact Restoration (COLOURS Scenario 1)

COLOURS Scenario 1, as defined in the Grant Agreement, starts from a gap in current restoration practice. Few tools let experts preview how a treatment would

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alter the colours of an object, although colour is central both to its historical and aesthetic significance and to the preservation of its materials. The gap concerns a wide range of museum objects, from polychrome sculptures, paintings and frescoes to textiles, historic photographs and films. The scenario therefore foresees a hybrid environment in which conservators, curators and heritage scientists, whether on site or remote, examine highly detailed digital twins together in virtual and XR spaces. There they can try out restoration options in real time, including their effect on colour and on the behaviour of materials, and assess them within a reconstruction of the setting for which the object was made. Viewing the reconstructed polychromy of a sculpture at real scale is a typical example. Working in a shared space also helps the whole team understand the reasoning behind each choice.

The online co-design workshops on the internal pilots (Section 3.1) translated this scenario into concrete use cases. In the workshop on Pilot 1a, the Baroque painting Adoration of the Holy Cross, one group designed a hybrid remote expert commission. In this use case, conservation experts based in different places evaluate alternative cleaning, overpaint removal and format reconstruction options on a shared digital twin, drawing on diagnostic evidence and predictive simulations (E5). The workflow they described runs from the retrieval of evidence to diagnostic mapping, scenario creation, simulation, collaborative review and the recording of the decision (E8). In the workshop on Pilots 2a,b, the polychrome sculptures by J. A. Eglauer, participants built and compared alternative hypotheses on the original appearance of the objects, combining diagnostic evidence, reconstructions of lost colours and collaborative expert review (E7).

Building on the general needs and challenges outlined in Section 3.2, the COLOURS Scenario underlying the Collaborative Simulation Environment (CSE) points to a set of specific stakeholder needs. These concern the use of simulation, visualisation and evidence to support conservation-restoration decision-making.

1. Anticipating intervention outcomes. Conservation-restoration decisions are frequently irreversible, yet the visual consequences of a given treatment can rarely be assessed with confidence prior to application. Conservator-restorers therefore require the ability to visualise simulated outcomes of proposed

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treatments, such as the reconstruction of lost or altered polychromy, on high-fidelity digital twins of the object. In this way, the effects of different conservation-restoration approaches on colour and material appearance can be examined in advance and treatment can proceed from a well-founded understanding of its consequences.

2. Projecting and comparing alternative scenarios. Users need to generate several alternative simulations (***virtual restoration***) and project them onto the object's digital twin, or within a shared physical or virtual space, where they can be displayed in succession or side by side and communicated with remote partners. Grounding discussion on directly comparable visual outcomes, rather than verbal or abstract descriptions, allows the relative merits of each **approach or scenarii** to be assessed more rigorously and transparently.

3. Integrating heterogeneous evidence in decision-making. Each conservation-restoration hypothesis rests on a distinct body of evidence, including multimodal diagnostic data, historical sources and comparative documentation. Users need to retrieve and display this evidence alongside the simulation it supports, so that every specialist can present the data informing their interpretation at the moment the decision is under discussion. This linking of evidence and visualised outcome strengthens the scientific basis of each choice and makes the reasoning behind it explicit to all participants.

4. Evaluating outcomes within their original context. The historical and aesthetic coherence of different conservation-restoration practices can only be fully appreciated in relation to the context for which the object was conceived. Curators and conservators-restorers therefore need to evaluate simulated outcomes within a reconstruction of the object's original or intended context, at real scale and under plausible viewing and lighting conditions, through immersive XR environments or projection into physical space. Different conservation-restoration approaches can be then assessed within the object's initial perception, rather than in isolation from its spatial and cultural setting.

5. Enabling equal participation in hybrid sessions. Expertise relevant to conservation-restoration decisions is often distributed across institutions and

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countries. Experts unable to attend in person therefore need simultaneous access to the same simulations, data and contextual visualisations as on-site participants, and the ability to contribute to the evaluation on equal terms. Hybrid participation ensures that decisions draw on the full range of competencies required, independently of geographical or logistical constraints.

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4. Decisional stages

Carried out analyses of needs and requirements, described in previous sections and D2.1 on conservation-restoration processes, lead to a mixed decision-making model. Some decisions require real-time interaction between experts (synchronous), while others can be prepared, evaluated, documented, and reviewed asynchronously. The balance between the two models changes throughout the overall workflow.

The list of key decisions emerging in WP2 impacts what professionals should be able to do in the collaborative simulation environment (CSE) designed in WP4, and which functionalities should be offered to involved users to support or accelerate the overall workflow. Emerging stages for key decisions are grouped into the following sections, with explicit references to collaboration models.

4.1 Design and Planning

The overall process begins with the definition of the conservation project: objectives, intervention scope, project schedule, participants, responsibilities, and communication strategies. For a given artwork, it is necessary to establish what should be investigated, who should participate, what level of intervention is appropriate, and how the work will be organized.

This stage benefits from both collaboration modes (synchronous and asynchronous). Initial planning, documents, object records, legislation, previous documentation, and project proposals can be prepared and reviewed asynchronously. However, establishing shared objectives, assigning responsibilities, resolving conflicting priorities, and agreeing on the overall intervention strategy are better addressed through synchronous collaborative sessions among professionals.

4.2 Preliminary Inspection and Condition Assessment

The artwork in this stage is initially examined to establish its condition, identify degradation phenomena, and determine areas requiring further investigation. Main decisions are related to how the condition of the object should be interpreted, and which issues or areas require further analysis. Such inspection is

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predominantly synchronous, when conservators and other experts examine the physical object together. Experts can discuss observations immediately and establish a shared understanding of the artwork condition. The resulting photographic material, annotations, condition maps, and observations should be mapped and reported into the collaborative simulation environment (CSE) providing the possibility of examining the artwork asynchronously by (remote) specialists who were not present during the inspection.

4.3 Scientific and Technical Examination

Within this stage, scientific examination produces a large amount of heterogeneous information, including imaging, spectroscopic data, 3D documentation, material analyses, and mapped condition information.
Such data provide essential information on material composition, manufacturing techniques, deterioration processes, and previous conservation interventions, forming a base for conservation decision-making. However, their diversity, complexity, and volume pose significant challenges in terms of storage, accessibility, interpretation, and long-term preservation. Dedicated visualisation tools are required to facilitate the interpretation of complex datasets, while comprehensive metadata structures should ensure data provenance, traceability, and reproducibility of analytical workflows.

Scientific data should leverage on Colour Knowledge Repository (CKR) available in COLOURS, accessed by tools/services (including CSE and MuLaX).

This stage is characterised by several critical decision points that influence both the analytical strategy and the subsequent interpretation of results. Key decisions include:

- Which areas should be investigated or sampled?
- Which analytical techniques should be used?
- How should the resulting analytical evidence be interpreted?

The outcomes of these decisions have a direct impact on subsequent phases of the conservation workflow, particularly diagnosis, intervention planning, and long-

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term monitoring. Consequently, the CSE should support not only data storage and retrieval but also collaborative interpretation and the integration of analytical evidence with condition assessments, historical documentation, and conservation records. Such functionalities are essential for ensuring transparency, traceability, and evidence-based decision-making throughout the conservation process.

Data processing and individual analysis in the virtual environment can largely occur asynchronously. Specialists can examine datasets, annotate 3D models, compare images, and prepare analytical reports independently. An emerging requirement involves the possibility of automating some of the conservation documentation (such as condition reports), thus providing an accelerator for these tasks.
CSE should accelerate condition report generation by automatically incorporating information already available within the collaborative environment (CKR, MuLaX), such as object metadata, analytical results, images, annotations, and records of previous interventions. The CSE should also support the creation of condition reports through annotations directly linked to 2D and 3D object representations, enabling the spatial documentation of condition issues and treatment areas. This would reduce repetitive manual data entry and improve documentation consistency. Furthermore, existing digital reports should be reusable and updatable within the system, facilitating the transition from traditional paper-based documentation towards a more integrated, interoperable, and continuously maintained conservation record.

However, the selection of analytical methods and sampling areas can have significant consequences for the artwork and therefore requires careful collaborative evaluation. Such decisions are particularly suited for synchronous collaborative sessions, involving conservators-restorers, heritage scientists, and other specialists to collectively assess risks, benefits, and analytical priorities.

4.4 Diagnosis and Interpretation

The diagnosis and interpretation stage represents the point at which the diverse forms of evidence collected during previous phases are integrated into a coherent understanding of the condition of the cultural heritage asset. Visual observations, scientific and technical examination results, historical documentation, environmental data, and records from previous interventions must be brought together and analysed within a common interpretative framework.

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This stage constitutes one of the most critical decision-making steps of the conservation workflow and is characterised by a predominantly synchronous collaborative approach. Unlike previous phases, where data acquisition and documentation activities may often be conducted independently and asynchronously, diagnosis requires the simultaneous involvement of different experts to discuss, compare, and interpret evidence in real time. The interpretation of complex and sometimes ambiguous observations greatly benefits from direct interaction among stakeholders, making this stage one of the most significant synchronous collaboration points within the entire conservation process.

Heritage scientists, restorers-curators, art historians, and other specialists can jointly examine the integrated datasets in the CSE and discuss alternative interpretations. The resulting consensus can subsequently be recorded and reviewed asynchronously.

To support this collaborative process, the CSE should allow users to view, compare, and discuss different types of information within a shared environment, including scientific results, condition assessments, historical documentation, and monitoring data. Experts should be able to annotate datasets, exchange observations, and contribute to the interpretation of the evidence.

Once a shared interpretation has been reached, the diagnosis and the supporting evidence should be recorded within the platform. This ensures that decisions remain accessible, traceable, and available for future consultation.

The outcomes of this stage provide the basis for conservation planning and intervention design.

4.5 Proposal for Conservation Intervention

Once the diagnosis has been established, the team develops possible conservation interventions within such stage. At this stage, the objective is to define the most appropriate intervention by considering factors such as conservation principles, material compatibility, potential risks, historical significance, expected benefits, and long-term preservation goals. The central question emerging from this stage is: which intervention should be undertaken, and to what extent?

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Different stakeholders may have different perspectives and priorities. Conservators may prioritise material stability, while curators, owners, historians, or funders may have additional aesthetic, historical, or practical concerns. As a result, the definition of the intervention often requires discussion and negotiation among participants. Collaborative environments can support this stage by enabling the sharing and review of proposed intervention scenarios.

Proposals can be prepared and circulated through an asynchronous model, allowing participants to study the alternatives and provide comments. The final negotiation and approval of the intervention scope should be conducted in synchronous collaborative sessions.

4.6 Testing and Mock-ups

Before applying a treatment to the object, alternative materials and methods can be tested on representative areas or mock-ups. The main topic within this stage is which treatment methods, material, or combination of materials produces the most appropriate result while minimising risk to the object. The simulation itself can be conducted collaboratively, particularly when experts need to observe the specific behaviours together. The resulting images, measurements, colorimetric data, and analytical results can subsequently be shared for asynchronous evaluation. This stage is particularly important for a colour-restoration workflow because alternative colour reconstructions can be generated and compared in a simulated environment before any intervention is undertaken.

4.7 Implementation of Conservation Treatment

Within this stage, the selected conservation treatment is applied to the physical artwork. Overall decisions revolve around whether the planned methodology remains appropriate as the treatment progresses, or whether it needs to be adjusted. The actual treatment is inherently synchronous, since conservators and restorers are physically working on the artwork in the physical space. However, the collaborative simulation environment (CSE) can provide continuous asynchronous oversight, allowing other specialists to review documentation, images, measurements, and treatment progress. If unexpected phenomena appear during treatment, a new decision point can be triggered. For instance, the discovery of an unexpected paint layer could require the treatment to be paused and the methodology reconsidered.

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4.8 Final Reporting and Archiving

After treatment, the collected information is consolidated into the final conservation record. The key decisions in this stage are:

- Has the intervention achieved its intended objectives?
- Which information should become part of the permanent conservation record?
- Which datasets can be shared openly and under what conditions?

The production of reports, metadata, derivative datasets, images, and documentation is primarily asynchronous. Different experts can contribute independently and review the material at different times. A collaborative validation session can then be used to establish agreement on final reports and the information that should be archived or made available to external users.

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5. Emerging requirements for the Collaborative Simulation Environment

What emerges from decisional stages discussed in previous section is a hybrid collaboration model, where not every activity needs to be synchronous.

- *Synchronous collaboration* should be focused on high-value key decisions, where different forms of expertise need to be negotiated and consensus established.
- *Asynchronous collaboration* should support the process by allowing participants to prepare evidence, annotate datasets, compare alternatives, document decisions, and review results at different paces.

This distinction is particularly relevant for the design of the Collaborative Simulation Environment (CSE) *building blocks*: its virtual spaces should not simply reproduce a physical meeting, they should act as a persistent, online, shared decision space - where the state of the artwork, evidence, alternative restoration scenarios / variants, previous decisions, and expert annotations remain available between different sessions. Every important conservation decision should be connected to the evidence, alternatives, participants, discussion, simulation results, and outcome that contributed to that decision.

An emerging model for collaboration across time is *bichronous* collaboration. The term originated in the field of online learning (Martin et al. 2020), where it denotes the intentional combination of asynchronous and synchronous activities within the same learning process. More recently [Giovannelli et al. 2025] extended the concept to collaborative virtual environments (CVE), describing a bichronous collaborative state as one in which archived contributions are integrated into an ongoing real-time collaborative session. This perspective moves beyond a binary distinction between synchronous and asynchronous collaboration and frames collaborative time as a continuum between these two extremes.

Bichronous collaboration should not be interpreted as a fixed or equal combination of synchronous and asynchronous activities, though, it represents an intermediate

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and variable position on a collaborative time continuum ; its position along the continuum varies according to the relative prominence of live interaction and archived annotations or recorded contributions.

Table 2 lists the requirements for the collaborative environment. Requirements COL-CE-01 to COL-CE-15 derive from the analysis of the decisional stages (Section 4). Requirements COL-CE-16 to COL-CE-24 complete the set: they cover needs identified in Section 3, contents required by the Grant Agreement for the collaborative environment (T2.4, T4.3), and commitments set out in D7.1.

Each requirement has:

- an identifier;
- A description:
- a source: evidence codes from Table 1, sections of this deliverable, or other COLOURS documents. Requirements that originate from design considerations rather than stakeholder input are marked "design input";
- an indicative priority;

Requirements were given an initial priority using the MoSCoW scheme (MUST, SHOULD, COULD, WON'T for this iteration), applying the criteria adopted in D2.1 (Chapter 5): relevance to conservation-restoration workflows, potential impact on practice, and technical feasibility within the project timeframe. Relevance and impact were assessed on the basis of how often and how strongly each need recurred in the workshop and survey evidence. Technical feasibility will be assessed in the internal pilots, using the data available for each case study, since it depends both on the current capabilities of the tools and on the type and quality of the available data (D2.1, chapter 5). The priorities in Table 2 are therefore indicative. They will be confirmed or revised on the basis of the pilot results, and the final prioritisation will be reported in the second iteration of this deliverable at M24.

The requirements will be validated in the internal pilots (T12.4) against the following indicators:

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- user satisfaction with collaboration workflows;
- time and effort saved in sharing and accessing data;
- effectiveness of communication and decision-making;
- real-time collaboration;
- version control;
- integration with the ECCCH.

Table 2: Requirements for the collaborative simulation environment. Priorities are indicative and will be confirmed after the feasibility assessment in the internal pilots; the final prioritisation will be reported at M24.

ID COL-CE	Requirement	Description	Source	Indicative Priority
01	HDT Management	The environment should provide a high-fidelity digital representation of the physical heritage object	E5; §3.4; D3.1	MUST
02	Observation	Users should be able to inspect the digital replica collaboratively in 2D, 3D and immersive environments enabling different stakeholders to access, explore, and discuss conservation-related information according to their specific needs and expertise.	E1, E5	MUST
03	Spatial Annotations	Users should be able to annotate points, regions and individual restoration areas directly on the 2D,3D model of the artwork, linking observations, condition assessment data, and documentation of past and ongoing conservation treatments to specific locations on the object.	E6, E7; §4.2	MUST

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		Annotations could include textual descriptions, photographs, analytical data, monitoring results, and treatment documentation, creating a comprehensive record associated with each area of interest.		
04	Multi-layer data integration	The CSE should allow users to combine and compare heterogeneous datasets, retrieving data from CKR, external repositories or other services/tools. Users should be able to explore datasets, overlay complementary information, and correlate observations derived from different investigations or time periods. Such functionality would support a more comprehensive interpretation of the object's condition, materials, and conservation history	E3, E7	MUST
05	Analytical Workspace	The virtual environment should provide tools for measurement, comparison, segmentation, material identification, spatial mapping. It should thus be able to integrate processes from other COLOURS services/tools.	E3	SHOULD

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06	Reporting	The CSE should be able to support the semi-automated production of reports (e.g. condition reports) associated with a given artwork, during the sessions. It should also support the integration of existing condition reports, promoting the transition from standard paper-based documentation to a digital, interoperable, and continuously updatable conservation record.	E2; E11; §4.3; D2.1	MUST
07	Evidence-Based Interpretation	The environment should enable experts to develop and share interpretations by integrating multiple evidence sources. Each interpretation should be linked to its supporting evidence, including the author, date, confidence level, comments, alternative hypotheses and relevant references	E6, E7; §3.4; D7.1	MUST
08	Alternative Intervention Scenarios	Users should be able to explore and compare multiple conservation scenarios before selecting a treatment strategy. CSE should support the evaluation of the expected impact, risks, and benefits of alternative interventions, enabling informed and collaborative decision-making among conservators, scientists, curators	E5, E7; §3.4	MUST
09	Virtual Restoration Simulation	The environment should allow users to simulate potential conservation/restoration interventions before applying them to the physical object/artwork. All simulations should be non-destructive.	E5; §3.4; GA T4.1	MUST

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10	Immersive Evaluation	CSE should provide an XR toolkit for VR and AR inspection of the virtual space.	E7; §3.4; GA WP4, T4.3	MUST
11	Explicit Decision Management	The CSE should represent decisions as explicit entities within the conservation workflow. Each decision should be linked to the questions addressed, the participants, the supporting evidence, the discussion process and the confidence level. Each decision should also be traceable, allowing to understand the decisions taken and review alternative options.	E6, E7; D7.1	MUST
12	Consensus	Different decision mechanisms could be supported, for instance: expert agreement, designated authority, advisory option	§3.2; design input	COULD
13	Real-time multi-user collaboration	The virtual environment should support simultaneous participation by multiple users (synchronous collaborative sessions). Multiple sessions should be supported in different virtual spaces.	E1, E5; §3.4; GA WP4	MUST
14	Persistent Workspace	Users should be able to contribute without being simultaneously connected (asynchronous collaboration), thus providing mechanisms to persistently store their processes/reasoning.	§5.1; design input; D3.1	MUST
15	Treatment Outcome Evaluation	After a physical intervention on the artwork, the actual result should be compared against the HDT, selected simulation, expected result – providing a feedback mechanism for improving future simulations.	Design input	COULD

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16	Data Upload	Users should be able to upload analytical and documentation data through a guided procedure, with format validation and metadata entry, so that the data become available to the CSE and the other COLOURS tools.	E4; §3.2; D2.1	MUST
17	Versioning and Snapshots	The CSE should keep versions of scenarios, annotations and decision states, including snapshots that can be retrieved and compared.	E6, E7; design input	MUST
18	Roles and Permissions	Access to spaces, sessions, annotations and datasets should be governed by role-based permissions derived from the COLOURS Platform login and roles, with no separate user accounts. Session owners should be able to invite remote experts with a defined role.	E6, E10; §3.2; D7.1	MUST
19	Project Space and Tasks	Users should be able to set up a shared space for a conservation project, defining participants, responsibilities, tasks and schedule, and to be notified of new contributions.	§4.1; GA T4.3	SHOULD
20	Controlled Vocabularies	Annotations, interpretations and decisions should use controlled vocabularies aligned with the CKR metadata schemas and the ECHOES Heritage Digital Twin Ontology.	§3.2; GA T2.4;	SHOULD
21	User profiles	The interface and the functions exposed should adapt to the user's profile (e.g. conservator-restorer, heritage scientist, curator, collection manager), including a simplified mode for users with limited digital experience.	E9; §3.2	SHOULD

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22	Sessions replay	Participants in a live session should be able to retrieve, replay and discuss contributions recorded in earlier sessions.	E8; §5.1	COULD
23	Decision Packages	Users should be able to export decision packages (compared scenarios, supporting evidence, decision record, participants) to share outside the environment, e.g. with commissions, owners or authorities.	E6, E7	SHOULD
24	Publication and licensing	Users should be able to select which records, datasets and decisions are published, with licence and access conditions, through the CKR to the ECCCH Knowledge Base.	E10; §4.8; GA T2.4; D7.1	SHOULD

Within the COLOURS project, *bichronous* collaboration can be interpreted at the workflow level, when it connects asynchronous preparation, live collaborative work, information capture, asynchronous review, validation and documentation, and at the session level, when current participants retrieve, inspect and discuss contributions produced during earlier activities or sessions.

Bichronous collaboration therefore involves more than simply alternating asynchronous and synchronous activities: it allows information produced in the past to become an active component of present collaborative work.

In the context of cultural heritage conservation, this model may support continuity across distributed, interdisciplinary and iterative activities it combines the immediate clarification and coordination of attention enabled by live collaboration with the persistence, revisability, and depth of specialist input afforded by asynchronous contributions.

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6. Conclusions and Next Steps

Decision-making in Conservation-restoration processes is collaborative by nature, but itis currently supported by fragmented documentation. Professionals and institutions exchange separate reports in heterogeneous formats; analytical data, observations and decisions are rarely kept together; and the reasoning behind a choice is difficult to reconstruct later.

The analysis of the decisional stages shows that not every activity requires real-time interaction. Synchronous sessions are most valuable at the points where expertise must be negotiated, such as defining objectives, selecting analyses, establishing a diagnosis and agreeing on the intervention. Preparation, documentation and review can largely take place asynchronously. The collaborative environment must therefore connect the two modes through a persistent record, rather than simply reproduce a physical meeting online.

The requirements defined in Chapter 5 translate this model into capabilities of the CSE, supported by the COLOURS Platform for identity and roles and by the CKR for shared data, versioning and publication to the ECCCH.

The requirements with the highest indicative priority concern:

- collaborative inspection and annotation of the digital twin;
- integration of heterogeneous evidence;
- comparison of alternative scenarios and simulation results;
- explicit and traceable decision records;
- real-time and persistent workspaces;
- role-based access.

The requirements are the starting point for D4.1 (M14), which will specify its components and architecture. The allocation of reporting functions between the CSE and MuLaX, and possible data exchange with OCRA, will be addressed there.

- **Integration and testing**: They are consistent with the integration and test plan (D7.2) and with the interoperability requirements set out in D7.1, and will be taken into account in their updates.

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- **Internal validation**: In T12.4 (M13–M24), the collaborative environment will be tested on the internal pilots. The indicators will be user satisfaction with collaboration workflows, time and effort saved in sharing and accessing data, effectiveness of communication and decision-making, real-time collaboration, version control and integration with the ECCCH.
- **Second iteration**: A second iteration of this deliverable will be produced at M24. It will report the final prioritisation, based on the feasibility assessment carried out in the internal pilots, and update needs and requirements in light of the pilot results, extending the evidence to the object types not yet covered.

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