Analysis of needs and requirements for advanced digital tools to support conservation

Deliverable 2.1

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Executive Summary

This deliverable presents the results of the first cycle of stakeholder engagement carried out within COLOURS Work Package 2, aimed at identifying and prioritising the needs and requirements for advanced digital tools supporting the conservation and restoration of light-sensitive cultural heritage, namely coloured collections. Building on the methodological approach developed by the PERCEIVE project (Deliverable D2.2) and aligned with the community engagement principles adopted in ECHOES-ECCCH (Deliverable D4.1), the analysis combines internal pilot feedback, structured workshops and focus groups with conservator-restorer partners. This deliverable is also closely linked to Deliverable D2.2 - Analysis of needs and requirements for an on-cloud collaborative environment to support conservation - restoration workflows, as both draw on the same stakeholder engagement process and jointly define the full set of user needs - functional and collaborative - underpinning the tools and environment to be developed within COLOURS.

The report is organised around the three core COLOURS scenarios – predictive and simulation-based restoration technologies, advanced digital tools for restoration and conservation practice and enhancing public engagement with restored colours – and translates the needs expressed by conservators-restorers and other stakeholders into a first set of functional requirements for the tools under development. These requirements will be prioritised after a feasibility assessment on the internal pilots, reported in D10.2 (M24), and will inform the design, development and validation activities of Work Packages 3, 4, 5, 7, 10 and 12.

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List of Abbreviations

AAI – Authentication and Authorisation Infrastructure

API – Application Programming Interface

AR – Augmented Reality

CPK – Cultural Probe Kit

CPK – Cultural Probe Kit

C-R – Conservation-Restoration

CSE - Collaborative Simulation Environment

HCSE – See CSE

ECCCH – European Collaborative Cloud for Cultural Heritage

ECHOES – European Cloud for Heritage OpEn Science

EOSC – European Open Science Cloud

EU – European Union

GA – Grant Agreement

HDT – Heritage Digital Twin

HDTO – Heritage Digital Twin Ontology

HSI – Hyperspectral Imaging

IR – Infrared

ISPC – Istituto di Scienze del Patrimonio Culturale (Institute of Heritage Science)

LDE – Light Damage Estimator

MR – Mixed Reality

PACT – People, Activity, Context, Technology (design methodology)

POI – Point of Interest

SSO – Single Sign-On

TRL – Technology Readiness Level

UV – Ultraviolet

VIS – Visible

VR – Virtual Reality

WP – Work Package

XR – Extended Reality

XRF – X-ray Fluorescence

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1. Introduction

1.1 COLOURS as a key contributor to the Cultural Heritage Cloud ecosystem

COLOURS adopts a strategy for a community-first approach in the early stages of technical developments, engaging heritage researchers and professionals directly to verify their needs and define requirements before tool development proceeds. This approach resonates with the community engagement methodology adopted in ECHOES-ECCCH, (Prandoni et al. 2026), confirming the relevance of stakeholder-centered design as a shared principle across the Cultural Heritage Cloud ecosystem.

COLOURS addresses a more focused segment of that ecosystem: **tools and services for heritage researchers and professionals, with conservators-restorers as the primary user group**, alongside the institutions, scientific community, and policy environment that shape and support their work.

Integrating the COLOURS tool platform into the ECCCH Cloud addresses the professional isolation that is typical of conservation-restoration (C-R) fieldwork. While practitioners often work in small, isolated teams on site, this integration provides them with a secure, on-demand workspace that connects field operations with remote digital and human resources. Conservators can test diagnostic hypotheses based on visual inspection or conventional field assessments, run simulation scenarios and exchange preliminary interpretations in real time or asynchronously with interdisciplinary collaborators. Crucially, every step and assumption can be automatically contextualised and captured within their reporting pipeline, as can every intermediate raw or processed dataset. This streamlines fragmented workflows into an organised, traceable personal workspace.

1.2 COLOURS target groups – Communities

Before the project began, COLOURS identified specific target groups to consider in terms of their needs and requirements when developing the tools. These groups form a community around the heritage objects, as they are usually asked to

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collaborate, share data and knowledge, interpret their output, and make decisions by consensus. Therefore, the development of the tools considers not only the requirements of individual users according to their specialized operational needs and their roles, but also functionalities that will facilitate teamwork and collaboration.

Predefined COLOURS target groups (Technical Annex)

- Cultural Heritage Institutions:
  museum curators, museum professionals, etc.
- Cultural and Creative industries & professionals:
  conservators-restorers, curators, heritage experts etc.
- Scientific community (researchers & academia):
  heritage researchers, academia
- ECCCH and other relevant EU Networks & Initiatives
  ECCCH, ECHOES, Europeana, EOSC etc.
- Funders & policymakers
  EU/National & Local Authorities (Ministries of Culture and Heritage)
- General Public

During the first year of the project, COLOURS closely followed ECHOES' activities and consulted available resources to identify the needs and expectations of the Heritage Community from the CHC (ECHOES D4.1). Without deviating from the established methodology of addressing the specific needs of target groups, COLOURS sought to align with ECHOES' strategies of engaging user clusters based on their structural and behavioral characteristics.

ECHOES' approach stems from the Cultural Heritage Cloud's conceptual framework, which aims at delivering a single, integrated digital environment that transcends all heritage domains, siloed fields of expertise, institutional barriers and linguistic diversity. This environment brings together professionals to co-create and enhance heritage knowledge.

Rather than replacing existing affiliations, the Cultural Heritage Cloud complements them by uniting professionals through shared digital practices, needs, and collaborative tools. To bridge the gap between traditional heritage

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work and digital workflows, ECHOES has designed an 'Atlas of Communities'. This multi-layer framework maps actors using structural data, such as working status, organizational type, field of activity, and types of heritage assets, as well as behavioral patterns relating to digital practices and needs. In other words, it shows how professionals engage with digital tools and data, including practices related to data creation, documentation, storage, sharing, reuse, collaboration with technical actors, responsibility for infrastructures, and perceived barriers. These patterns form relatable user clusters, or 'personas', such as data producers, developers, managers, and policymakers, capturing the hybrid, evolving roles within the cultural heritage ecosystem without disrupting institutional mandates.

From this perspective, the COLOURS target groups, which represent affiliations based on disciplines or professional activities or roles, are mapped onto the CHC Atlas of Communities. This creates a more fluid, digital, practice-oriented model of collaboration and inclusion. This approach establishes an additional layer of connection based on common needs, expectations, and modes of engagement with digital environments. In this sense, the Cloud does not replace disciplinary specificity, but rather complements it by fostering a transversal, federated community constituted of existing communities and networks across the cultural heritage landscape, as understood through the lens of their digital practices and literacy.

Such an approach aligns with COLOURS' aim of engaging users from a variety of institutional frameworks, professional statuses and disciplinary backgrounds-including freelancers with limited or no access to diagnostic data, as well as conservators-restorers working in museums and institutions with greater access to such data. It also addresses the varying levels of digital skills and readiness among these groups.

A key aim underpinning this engagement strategy is to facilitate more effective collaboration between heritage researchers and conservators-restorers, through the digital tools' developer within COLOURS. The two professional groups, while operating with distinct methodological and institutional frameworks, share a common interest in the study, documentation, and preservation of colour-sensitive artefacts. The tools envisaged by COLOURS are therefore designed not

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merely to serve each discipline in isolation, but to act as a shared digital interface, supporting the exchange of data and expertise, encouraging a more integrated and mutually reinforcing workflow.

The table below re-groups the six main target communities of COLOURS along sector-facing lines, while explicitly mapping each one to the ECHOES cluster(s) it corresponds to. This preserves continuity and comparability between the two projects' community-mapping work, showing where COLOURS narrows on practitioner-facing needs, which are treated as a broader, ecosystem-wide level by ECHOES.

***Table 1**: COLOURS target communities and Corresponding ECHOES Clusters.*

Target community	Description	Key Characteristics	Main Needs	Corresponding ECHOES Cluster(s)
Cultural Heritage Institutions (museum curators, museum professionals, conservators-restorers, etc.)	Institutional actors managing collections, exhibitions, and long-term stewardship of heritage assets within museums and similar organisations	Institutional workflows, reliance on internal repositories and policies, collection-centered priorities, varying degrees of digital maturity	Controlled access and storage, governance support, tools that fit existing institutional processes (usability, workflow integration, standards, training)	Institutional Anchors; Professional Heritage Practitioners; Cultural Communicator (Museum educator)
Cultural and Creative Industries & Professionals (conservators-restorers, curators, heritage experts, etc.)	Practice-based professionals directly engaged in the conservation, restoration, documentation and interpretation of heritage objects and sites — **project's**	Hands-on, practice- and compliance-driven workflows; domain-specific methods; variable digital tool adoption; operating across a spectrum from	Usable, standard practice-adapted digital tools; tools that fit existing institutional processes (usability, workflow integration, standards,	Professional Heritage Practitioners; Freelance/Self-Employed; Cultural communicators Varying degrees of digital maturity

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	primary user group	freelance practice to institutional employment	training); affordable tools and infrastructure access	
Scientific Community (researchers & academia) (heritage researchers, academia)	Research-oriented actors producing, analysing, and disseminating scientific and scholarly knowledge related to heritage materials, heritage science and digital methods in academic contexts.	Research-driven workflows, data-intensive and analytical practices, mixed digital practices, engagement with advanced software and analytical techniques	Interoperability, reusable datasets, metadata support, advanced tools, scalable infrastructure, training	Academia and Research; Data Producers (Scientific); Technical Developers
ECCCH and Other Relevant EU Networks & Initiatives (ECCCH, ECHOES, Europeana, EOSC, etc.)	Networks, infrastructures and sister initiatives operating at EU level to support open, interoperable, and sustainable heritage data ecosystems	Cross-project coordination, focus on interoperability and open infrastructures, advocacy and alignment role, policy-adjacent positioning	Alignment on standards and FAIR principles, sustainable shared infrastructures, coordination mechanisms, visibility of complementary project outputs	Data managers; Open Data & Policy-Oriented;
Funders & Policymakers (EU/National & Local Authorities, Ministries of Culture and Heritage)	Public bodies and authorities shaping funding priorities, regulation, and policy frameworks for cultural	Governance and policy focus, long-term strategic orientation, engagement with evidence and impact rather than day-to-day	Clear evidence of impact and uptake, licensing and policy clarity, alignment with fair and open-data principles,	Policy, Governance & Cultural Sector Support

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	heritage and its digital transformation	tool use	sustainable outcomes to inform future funding decisions	
General Public	Non-specialist audiences engaging with heritage content and outputs for learning, cultural enrichment, or personal interest	Low to moderate digital/domain expertise, engagement mediated through accessible content and interfaces, informal interaction patterns	User-friendly access, curated and rights-cleared content, simple tools, basic guidance/support	Low-Digital Users

1.3 Conservator-restorers in the European Collaborative Cloud for Cultural Heritage (ECCCH)

ECHOES, the project building the ECCCH, is organised around four pillars (Communities, Knowledge, Innovation and Sustainability) and a cross-cutting pillar. The Communities pillar seeks to bring researchers, heritage professionals and technology providers together around the Cloud, to understand their practices and needs so that the services developed respond to them, and to support uptake through a community-led training programme (ECHOES, Activities, https://www.echoes-eccch.eu/activities/).

Conservators-restorers are a pillar of the ECCCH community and are therefore at the heart of the Heritage Cloud development, which aims to understand their needs and provide tools and services to support C-R community practices, improving the efficiency and quality of current workflows.

According to the findings of the ECHOES consultation analysis, which allows for the investigation of consultation data from different perspectives, the main CH Occupation categories were identified, providing a structured overview of the communities represented and supporting the interpretation of occupational backgrounds, sectoral needs and potential areas for targeted services, engagement actions and capacity-building within the ECCCH.

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The consultation received considerable response from conservation and restoration professionals, demonstrating that these experts are keen to contribute to cloud development. Of the 1,303 responses to the ECHOES survey that were considered exploitable for community mapping, 825 responses were exploitable for the analysis of digital practices and needs, and 806 responses were fully completed. Of these, the conservation-restoration community, is represented by 140 full responses, including specialists involved in the physical preservation, restoration, scientific analysis, and long-term safeguarding of cultural heritage assets, buildings, and collections. Examples: Conservator, Conservator-restorer, Conservation scientist, Conservation architect, Heritage architect, Heritage consultant, Heritage technician, Historic Environment Officer. Of these, 125 (89%) identify their professional activity to primarily fit within the field of cultural heritage conservation and preservation.

The findings reveal a heterogeneous and still developing adoption of digital tools within the profession. Among the respondents, only 39% currently use data annotation and analysis tools or services, only 34% of respondents currently use 3D modelling and visualisation tools or services and only 23% are using formal knowledge representation tools or services. At the same time, 41% of the respondents would like to use tools for manual annotation of digital assets, such as text, images and 3D models. Among the main difficulties conservator-restorer professionals encounter when using digital tools and resources, 21% point to cost and licensing, while 15% identify the learning curve and lack of training.

1.4 COLOURS objectives addressed in WP2

COLOURS is structured around four functional scenarios that reflect the project's specific goal to support the community in aligning with the digital transition in the conservation and restoration of cultural heritage. In each scenario, internal pilots guide the development, integration and validation of the associated tools. A number of case studies, representative of different object typologies, form the basis of the internal pilots for each COLOURS scenario.

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- **Scenario 1**: A collaborative decision-making environment for museum artefact restoration involving tools that support shared decision-making among restorers, curators and scientists.
- **Scenario 2**: Simulation and predictive restoration. This scenario involves tools for visualisation and simulation of restoration outcomes before physical intervention.
- **Scenario 3**: Advanced digital tools for restoration, such as adaptive tools for colour analysis, documentation and processing.
- **Scenario 4**: Public engagement with restored colours, involving tools to foster access, transparency and storytelling using immersive and interactive technologies.

COLOURS Scenario 1 is not analysed in this deliverable. The needs and requirements associated with this scenario, relating to shared decision-making among conservator-restorers, curators and scientists within an on-cloud collaborative environment, are addressed in Deliverable D2.2 – Analysis of needs and requirements for an on-cloud collaborative environment to support conservation-restoration workflows. Both deliverables draw on the same stakeholder engagement process, and the requirements defined in D2.2 provide direct input to the design of the Hybrid Collaborative Simulation Environment developed in WP4.

Although the pilots are primarily designed to test and validate the functionality of COLOURS' digital tools, they were also conceived as a practical application to define user requirements for each tool category, as defined in the COLOURS scenarios. Using a bottom-up approach, use cases enable the generation of a generalised pipeline of conservation workflows, the formalisation of the lifecycle of conservation activities, and the identification of gaps and needs that the project outcomes will fulfil to improve workflows in terms of effectiveness and quality.

The tasks in Work Package 2 (WP2), which aim to collect, analyse and prioritise user needs, have been developed with reference to selected specific use cases.

During the first year, activities focused on engaging with stakeholders to describe, document, and analyse the needs and expectations regarding solutions provided by digital tools. Representative case studies were proposed by specialist partners

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for this purpose. These case studies, which were pre-selected within the GA, were expanded upon in some instances to help lay the foundations for the project's pilot activities. This ensured that they reflected the key needs and priorities of the cultural heritage community whilst maintaining their practical relevance. An iterative feedback loop established through the internal pilots has enabled the COLOURS project to gather and assess user feedback on the relevance, usability, and applicability of its tools regarding current conservation-restoration challenges. This process has provided valuable input for the identification of potential refinements and future functional enhancements, while helping ensure that the tools remain scalable, user-friendly, and suitable for broader uptake across the cultural heritage sector. The resulting feedback will inform the next stages of development and support the further fine-tuning of the tools and methodologies to maximize their real-world applicability and long-term impact. To ensure the development of credible and sound pilot frameworks from the outset, exemplary case studies provided by cultural heritage partners like ***Bratislava City Gallery***, ***Brakebusch Conservation Studio***, the ***Institute for the Protection of Cultural Heritage of Slovenia***, as well as the ***Italian Ministry of Culture*** have been identified.

Across all engagement activities, particular attention was given to capturing the perspective of conservators-restorers as the primary intended users of the COLOURS digital tools, ensuring that their operational workflows, professional judgement, and practical constraints remain central to the definition of needs and requirements presented in this deliverable.

The remainder of this deliverable is structured as follows: Section 2 describes the methodological approach adopted for stakeholder engagement; Section 3 presents the needs identified for each COLOURS scenario considered, together with the resulting use-case analysis; Section 4 translates these needs into functional requirements for each tool; Section 5 describes the prioritisation approach, which will be applied after the internal pilots and reported in D10.2; and Section 6 draws conclusions and outlines the next steps for Work Packages 3, 4, 5, 7 and 10.

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1.5 Relationship with other Workpackages

The output of D2.1 will directly inform and support the work of several other Work Packages:

- WP3 (Technology Adaptation & Development). D3.1 incorporates the needs and requirements identified in WP2. The requirements in Section 4.3 are the input for that revision, for the second iteration of D3.2 on predictive analysis and simulation tools (M24) and, for the CKR, for D3.3 on repository design and HDT mapping (M18).
- WP4 (Hybrid Collaborative Simulation Environment): the needs and requirements defined for an on-cloud collaborative environment to support conservation-restoration projects [Objective 4.4], captured in **Deliverable 2.2** - Analysis of needs and requirements for an on-cloud collaborative environment, provide direct input for the design of the Hybrid Collaborative Simulation Environment. The collaborative workflows, stakeholder expectations and interdisciplinary decision-making needs mapped in D2.2 inform how the HCSE is specified in Task 4.1, ensuring that its real-time collaboration capabilities and integration with existing workflows respond to needs already identified within the communities, rather than being defined independently.
- WP5 (Colour Management - Definition and Requirements) Requirements on colour representation, such as consistent rendering across devices (Section 3.6), are addressed by the colour management protocols of D5.1 and D5.2. The WP5 survey of photographers, conservators and restorers on current colour management practice complements the evidence of this deliverable
- WP7 (ECHOES-ECCCH Interoperability & Integration: Requirements & Planning): the stakeholder and workflow insights gathered in WP2 inform how users will access and interact with the tools once made available on the cloud, ensuring that the integration strategy and testing framework developed in WP7 remain grounded in the actual needs and expectations of the community rather than being defined from a purely technical standpoint.
- WP10 (Internal Pilots: Application on case studies): the community engagement and needs analysis activities carried out within WP2 provide the

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foundational basis for the definition of the Internal Pilots, the core focus of WP10. The work performed within WP2 to date - documenting conservation-restoration workflows, identifying gaps and requirements in selected case-studies, and engaging stakeholders- has directly informed the scope, focus and design of the case studies addressed in WP10, ensuring continuity between the project's different stages and strengthening the coherence of the project's user-centered approach. WP10 will build on this foundation, with the progression and testing of the tools on the Internal Pilots expected to further solidify and refine the needs and requirements identified in WP2. In particular, WP2 and WP10 jointly assess the feasibility of the requirements identified in this deliverable on the case studies of the internal pilots, using the data available for each case study. The resulting prioritisation of the requirements will be reported in D10.2 (Internal Pilot Evaluation and Refinement Report, M24).

- WP12 (Testing and Validation). The requirements are the reference for the validation framework of the COLOURS tools (D12.1, M15) and for their internal validation on selected case studies (D12.2, M24).

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2. Methodology

2.1 Background

PERCEIVE[1] project, Perceptive Enhanced Realities of Colored collEctions through AI and Virtual Experiences aimed at advancing the digital capability of scientists and cultural institutions through a service-based AI architecture and toolkit, and by developing a new design theory for on-site and remote VR/AR/MR experiences, based on the concepts of "Care", "Accessibility", and "Authenticity", with and for the creative industries, expanding the access to Cultural Heritage and Art outside museums for wider integration with society.

The project addressed the fragility and the dual needs of better preserving and communicating coloured artwork (paintings, sculptures, textiles, historical films and photos, and born-digital art) by improving and speeding up scientific process results, which could be employed to enhance preservation and maximise visitors' experience.

Based on the PERCEIVE theory of colour perception, study and representation, and the concepts of caring, authenticity and engagement, user needs and expectations were analysed in relation to PERCEIVE research and application scenarios.[2] [3]

The requirements for each digital tool were formulated based on the specific needs of various stakeholders. Stakeholders were categorised into six groups: 1) Museum Professionals, 2) Heritage Researchers, 3) Creative industries / Designers, 4) Citizens / Museum visitors, 5) Educators, 6) Decision Makers.

Their needs were mapped against key activities referring to colour studies workflows and behaviours, including: material characterisation and colour change detection; scientific analysis and acquisition (shape, colour and material acquisitions and diagnostics); interpretation; colour change monitoring (sensitivity detection, exhibition policy); reality-based reconstruction (2d and 3d reconstruction of shape, material, color); conservation vs access policy

[1] https://perceive-horizon.eu/
[2] Pescarin, S., *et al.* (2023) *Perceiving Coloured Collections: the PERCEIVE theory*.
[3] Pescarin S., *et al.* (eds.) (2025) *Chromatic Visions, Exploring Colour in Art, Archaeology and Digital Realities, Part I*.

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(identification and mitigation of risks); communication of results (experts and public audience); data transparency of processes and reliability of results. For each activity, the following were considered: main issues professionals face; involvement of different actors/professionals; complexity of the activity; required input data; produced output data.

After an extended survey, an insightful analysis of the user requirements, based on a prioritization process, was carried out and evolved by the working group of each scenario, using a composite methodological approach combining:

a. The PACT method (People, Activity, Context, Technology) and it is a way to enquire and let relevant elements emerge to define and prioritise the needs for each PERCEIVE tool or prototype, interrogating the relevant stakeholders (People), their context (Context), workflow/behaviours (Activities), needs, acceptable and available tools and services (Technologies) and requirements.
b. The Cultural Probe Kits (CPK)[4] [5].

The insights derived from this process, including the structured mapping of stakeholder needs against colour studies workflows and the prioritisation of tool requirements, represent a relevant methodological reference for the community engagement work carried out within ECHOES WP4. Full data is available in the public report.[6]

The work carried out in PERCEIVE directly feeds into COLOURS, an ECHOES sister project that builds on PERCEIVE's tools and methodology to develop a cloud-based toolkit for the conservation and restoration of coloured cultural heritage items. By extending the PERCEIVE approach into the Cultural Heritage Cloud environment, COLOURS targets conservators and restoration professionals as its primary user community.

[4] Benyon, D., *et al.* (2005). *Designing interactive systems: People, activities, contexts, technologies*.

[5] Pescarin, S., *et al.* (2023) *PERCEIVE Cultural Probe Kit on Caring attitude in XR experiences: activity book, diary and art practices for designers to explore and solicit care in Cultural Heritage domain* (Version 2).

[6] National Research Council, Foundation for Research and Technology Hellas (2023) *D2.2 Stakeholders needs and Requirement Analysis* (Version 2).

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2.2 Workshops and focus groups

To introduce COLOURS objectives and engage communities to the project developments aiming to impact on the digital transition of the conservation and restoration of cultural heritage objects, a series of workshops and focus groups were organized, bringing together conservators-restorers, researchers and technical developers with direct experience in the treatment of coloured artifacts. These activities were designed to foster dialogue between end-users and technical developers, enabling the collection of first-hand insights into current conservation-restoration workflows, existing gaps and pain points, and expectations towards the adoption of advanced digital tools. Particular emphasis was placed on gathering practice-based knowledge regarding the current level of digital expertise among conservators -restorers, ensuring that the resulting requirements are firmly rooted in real-world operational contexts. The outcomes of these engagement activities complemented the requirement analysis primarily developed through the project's internal pilots, jointly informing the needs and requirements presented in this deliverable and bridging the gap between technological innovation and the practical demands of the cultural heritage sector.

The following workshops and focus groups were organised as part of this engagement process, each targeting specific stakeholder groups and aspects of the conservation-restoration workflow relevant to the COLOURS project:

2.2.1 COLOURS-ECCCH Workshop in Ljubljana: Shaping the Future of Digital Practices in Conservation-Restoration

Location: Archives of the Republic of Slovenia (Poljanska street 40), May 12th, 2026.

The workshop introduced participants to the COLOURS-ECCCH Community of Practice and its suite of digital tools designed to bridge the gap between conservation-restoration expertise and digital efficiency. The aim of the workshop was to introduce the community of conservators-restorers to the COLOURS digital tools through interactions and demonstrations of the tools, and to subsequently collect their feedback in order to provide COLOURS partners and developers with substantial information on a realistic digital workflow that would be of genuine

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interest to end-users and could be effectively integrated into current normal working practices.

A survey was then disseminated to the participants, in order to collect feedback on the COLOURS digital tools demonstrated during the workshop: COLOURS Survey. Nine participants completed the survey. Their main areas of work were easel paintings (2), wall paintings (1), polychrome statues or objects (1), buildings (1), material analysis and microbiology (1), and several object types (3).

Workshop outcomes were then collected (Annexes): Ljubljana Workshop outcomes.



***Fig. 1**: presentations by conservator-restorer partners at the workshop*

The workshop also included presentations by conservator-restorer partners on their current digital practice. ZVKDS described a mainly field-based practice on wall paintings, façades and stone, in which general-purpose image-editing software is used for colour studies, graphic reconstructions and condition mapping. They identified cost, accessibility, lack of training, software complexity

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and limited interoperability as the main obstacles, together with field conditions such as dust and the lack of electricity and internet connection. GMB presented the documentation methods routinely used in its conservation department and the open questions of its pilot case studies and listed the weak points of current approach: fragmented and non-standardised documentation, poorly documented past interventions, lack of comparative material, limited access to analytical laboratories, long waiting times for analytical results and weak cross-disciplinary collaboration.

2.2.2 Online Consortium Workshops on the Internal Pilots

The COLOURS online consortium co-design workshops aimed to translate internal pilots and case studies into concrete, reusable and comparable use cases for conservation, restoration and public engagement. Bringing together conservator-restorers, researchers, curators, tool experts and digital heritage specialists, they focused on users, tasks, institutional goals and practical constraints. Two workshops have been organised, using a shared methodology to enable comparison across conservation contexts. They addressed:

1) Pilot 2a, b[7]: wooden polychrome sculptures collection by J. A. Eglauer (GMB).

2) Pilot 1a: Baroque easel painting *Adoration of the Holy Cross* (ZVKDS).

Each workshop combined a plenary session with interdisciplinary breakout activities. Following presentations of the conservation context, available evidence and unresolved questions, participants used online polling to prioritise use cases, audiences, goals and design requirements. Three groups then developed alternative storyboards on a shared online board using an adapted PERCEIVE CoDesign Tool. **These activities mapped realistic end-to-end workflows, identified combinations of COLOURS tools, and highlighted missing**

[7] Pilot numbering follows the current Internal Pilot list of WP10, which regroups the five pilots of the Grant Agreement into four: **Pilot 1** (paintings; GA Pilots 1 and 2), **Pilot 2** (polychrome 3D objects; GA Pilot 3), **Pilot 3** (XR presentation; GA Pilot 4) and **Pilot 4** (film frames; GA Pilot 5). The case studies of each pilot are listed in D5.2 (Table 4.1); their deployment will be also reported in D10.1 (M24).

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functionalities, content and datasets needed for subsequent development and validation.

The Bratislava workshop explored original appearance reconstruction, predictive restoration planning and public interpretation, while the Ljubljana workshop focused on cleaning hypotheses, format reconstruction and remote expert commissions. Together, they defined integrated toolchains connecting evidence retrieval and diagnostic visualisation with scenario comparison, simulation, collaborative review and public communication.

Key requirements included: **evidence-to-region linking, layered visualisation, version management, confidence and uncertainty representation, cleaning simulation, remote collaboration and traceable decision records.** The results helped shift the project from individual tool demonstrations towards integrated, evidence-based workflows organised around three complementary layers: evidence, decision-making and communication (complete description in Annexes).

2.3 Scope of the evidence base.

The evidence presented in this deliverable is qualitative and was collected from professionals directly involved in conservation-restoration. The Ljubljana survey (nine respondents) complemented the group sessions with the conservator-restorers attending the workshop; its figures indicate trends rather than statistically representative results. The co-design workshops examined two internal pilots in depth, an easel painting and a polychrome sculpture collection, and involved several COLOURS tools, while the workflow analysis (Section 3.2) covered the case studies of all conservator-restorer partners. Photographic and film materials, addressed by Neg2Pos, doLCE 2.0 and the Degreening Tool, are not yet directly represented and will be examined in Pilot 4 and, where relevant, in the external pilots. The tools were assessed as working prototypes, most of them inherited from PERCEIVE, while VarnishLab was presented as a proof of concept. The internal pilots will extend this evidence, and their results will be reported in D10.2.

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3. Stakeholder engagement and requirements analysis

Professionals operating within the cultural heritage sector are characterized by a stewardship-first orientation, in which the long-term preservation and ethical protection of heritage assets constitute the primary professional imperative. This orientation informs a value-led approach to practice, in which cultural significance, historical accuracy, authenticity, and societal benefit are prioritized over technological innovation as an end in itself. For conservators-restorers specifically, this stewardship principle is grounded in the **physical heritage object**: its material condition, its documented history of prior interventions, and its capacity to convey authentic knowledge over time. Digital and technical tools hold value for this professional community only in service of the object — enabling its documentation, informing conservation and restoration decisions, and preserving the evidence it carries. Such tools must consequently be conceived as instruments that support and reinforce the practitioner's direct engagement with the physical object, rather than substitutes for that engagement. This principle constitutes a foundational premise for the stakeholder engagement and requirements analysis presented in this chapter. It further accounts for a documented degree of caution within the sector regarding large-scale, cloud-based digital infrastructures, arising from legitimate concerns related to data ownership, privacy, intellectual property, and the long-term risks of digital degradation and obsolescence.

3.1 General needs

The identification of stakeholder needs and requirements was structured around a set of core pillars, which guided the analysis conducted along with conservator-restorer partners and framed the main dimensions along which their needs and requirements were examined and documented. These dimensions are summarized in the following points:

- Analysis of current conservation-restoration workflows, representative of typical conservation-restoration projects - documenting of activities' lifecycle
- Data flow preliminary analysis: Outlining how data is generated, processed, shared, and stored throughout the workflow; identifying data entry points,

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decision-making nodes, and outputs (e.g., reports, visualizations, or public exhibits)

- Understanding the challenges in preventive conservation
- Identification of needs and requirements, bridging of existing gaps in workflows and needs for digital tools integration
- Definition of areas of application of the existing COLOURS tools
- Discussion of needs for adaptation of the existing tools, extension with additional functionalities
- Discussion on the integration of tools within the workflow
- Definition of requirements for on-cloud collaborative environments

In analytical terms, the process moves from the identification of actors, activities and constraints within conservation-restoration workflows to the formulation of stakeholder needs and, subsequently, to the definition of capabilities that the digital environment should provide. These capabilities are then expressed as functional requirements and associated with the relevant COLOURS tools, often within Internal Pilot contexts. This structure also provides the basis for tracing each requirement back to the evidence from which it was derived.

Taken together, these dimensions provided the basis for translating the needs expressed by conservator-restorer partners into the functional requirements presented in Section 4, and for the prioritisation approach described in Section 5. The data flow analysis is addressed in a complementary manner by this Deliverable and Deliverable D2.2 – Analysis of needs and requirements for an on-cloud collaborative environment to support conservation-restoration workflows. While the present deliverable focuses on how data is required and produced by the COLOURS digital tools within the conservation-restoration workflow, D2.2 describes how information is currently exchanged among the actors involved in conservation-restoration projects. The definition of requirements for on-cloud collaborative environments is likewise addressed in D2.2.

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3.2 The digital dimension of a conservation-restoration workflow

In order to better situate the COLOURS digital tools within real conservation-restoration practice, an initial effort was made to establish a common conservation-restoration workflow together with the conservator-restorer partners involved in the project. To this end, partners were asked to complete a structured workflow template for each of their proposed case studies, describing the main phases, decision points, and operational steps characterizing their conservation-restoration processes. Although the specific nature of the case studies varied in terms of materials, condition issues, and intervention objectives, this exercise made it possible to identify a broadly shared and essentially linear workflow, spanning from preliminary documentation and condition assessment to diagnostic investigation, decision-making, treatment planning, practical intervention, and final documentation. The resulting workflow does not aim to flatten the complexity of conservation-restoration practice, but rather to provide a common reference framework through which recurring stages, needs, and opportunities for digital support can be identified across different contexts.

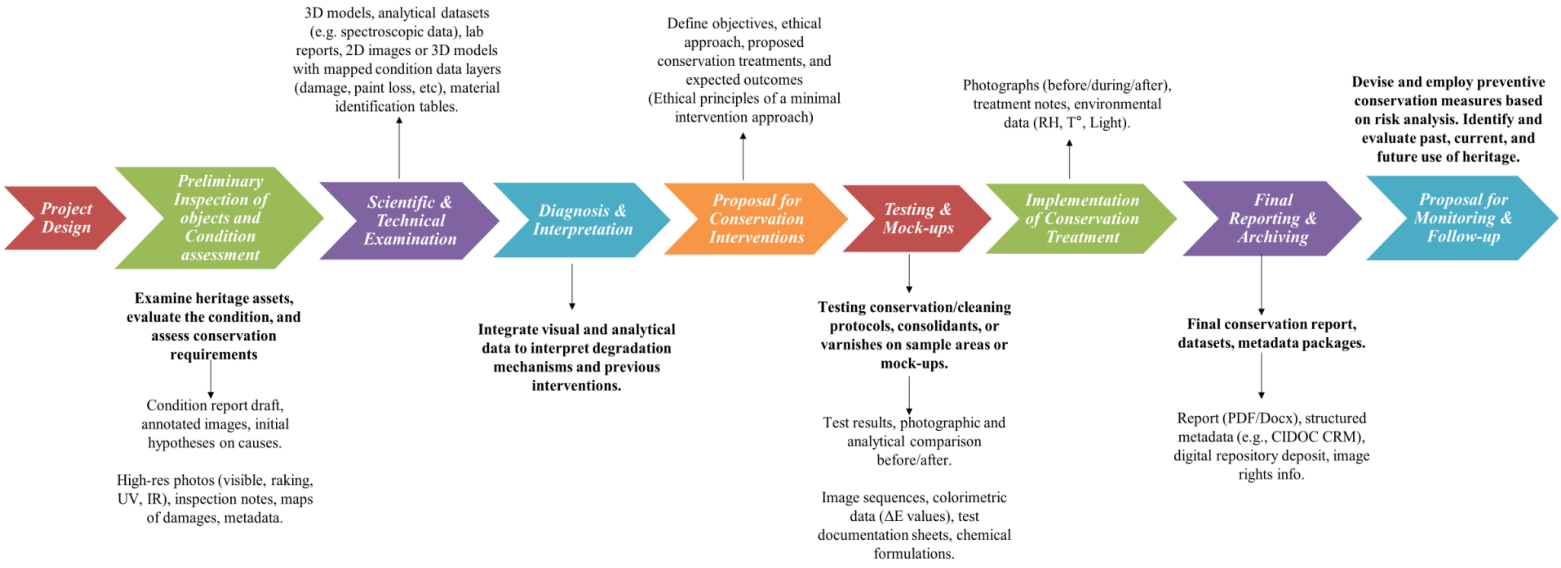


***Fig. 2**: Conservation-Restoration Workflow.*

Building on this shared workflow, a second step consisted in asking conservator-restorer partners to reflect on where, within these different stages, the digital tools developed in COLOURS could be meaningfully integrated. The objective was not

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simply to match tools to case studies, but to understand how they could be attached to specific moments of the conservation-restoration process in ways that respond to actual professional needs. In this sense, the digital dimension was approached as an integral part of the workflow rather than an external or parallel layer. Partners were therefore invited to indicate whether a given tool could support, for example, the interpretation of diagnostic data, the comparison of treatment alternatives during decision-making, the testing and simulation of possible conservation-restoration approaches, or the documentation and communication of intervention outcomes.

This mapping exercise was particularly important in clarifying the potential role of COLOURS tools across the workflow. Some tools may be most relevant in the analytical and interpretative phases, where material evidence and imaging data are examined to better understand the artefact's condition and conservation-restoration history. Others may contribute more directly to decision-making and treatment planning, for instance by supporting the visualization of expected outcomes, the evaluation of alternative treatment scenarios, or the assessment of how different conservation-restoration choices may affect the appearance and legibility of the object. In other cases, the added value of digital tools may lie in the trial and testing phase, where conservators-restorers explore possible approaches before implementation, or in the post-intervention stage, where they can strengthen documentation, traceability, and the long-term accessibility of knowledge generated during treatment.

The establishment of a common workflow and subsequent identification of possible points of digital integration therefore served two complementary purposes. First, they provided a structured basis for discussing conservation-restoration practices across a diverse set of internal pilots, making explicit the stages, needs, and decision points that characterize treatment processes. Second, they created a practical framework for assessing the relevance of COLOURS tools in relation to these workflows, helping to shift the discussion from generic digital potential to concrete forms of support within professional practice. In this respect, the digital dimension of the conservation-restoration workflow should be understood not as the replacement of expert judgement, but as the incorporation of digital methods

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and environments that can enrich observation, analysis, simulation, decision-making, and documentation. By grounding this reflection in the workflows provided by conservator-restorer partners, the project was able to approach tool integration from the perspective of real operational contexts and to begin identifying where digital support may be most effective, meaningful, and transferable across the wider cultural heritage sector, with the focus being placed on the community of conservators-restorers as the primary end-user group.

The workflow mapping also provides a reference structure for requirements analysis. Rather than treating requirements as isolated tool functionalities, each requirement can be associated with a specific phase of the conservation-restoration process, the actors involved, the information required or produced, and the decision or activity it is intended to support. This makes it possible to assess not only whether a function is technically desirable, but also where and why it is needed within professional practice.

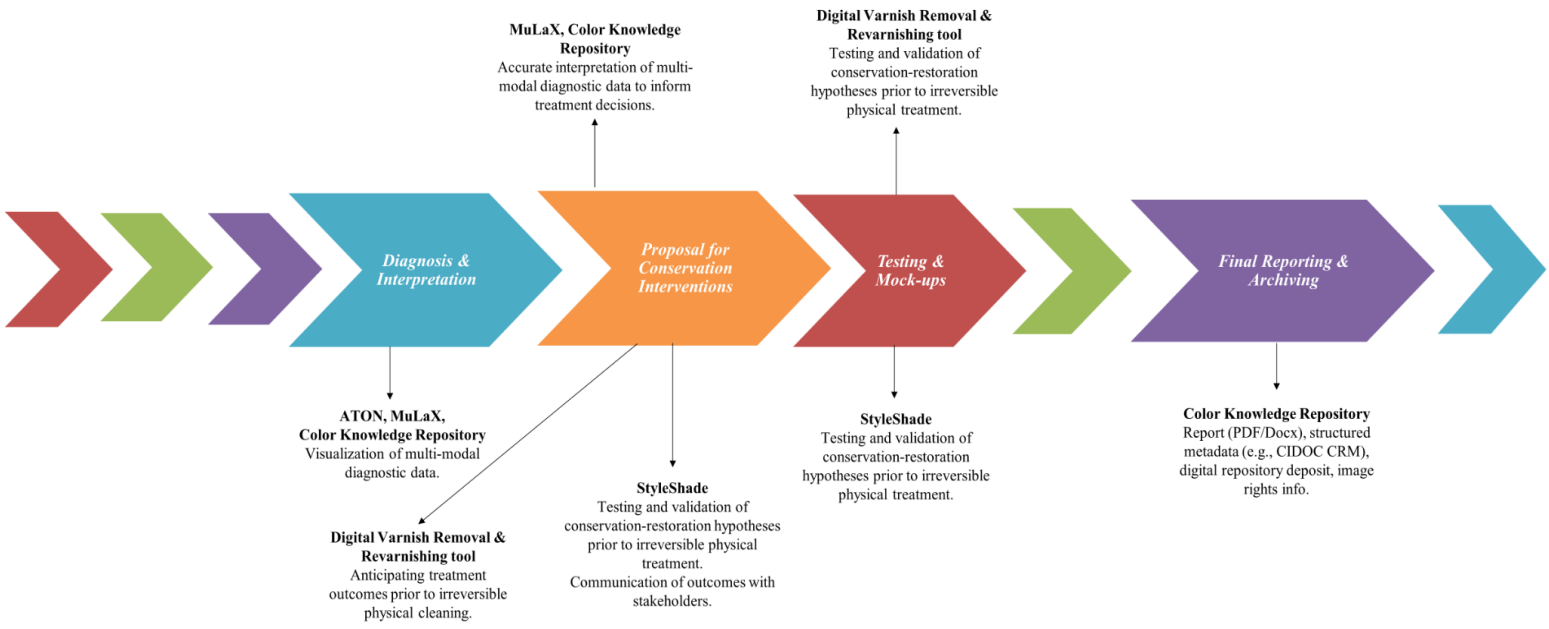


***Fig. 3**: Possible Integration of COLOURS tools in the Conservation-Restoration Workflow.*

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3.3 The Colour Knowledge Repository

The Colour Knowledge Repository (CKR), originally developed in the PERCEIVE project and expanded within COLOURS, is an open, scalable repository designed to manage and semantically enrich various types of digital resources (images, 3D models, datasets, texts, presentations, publications, workflows, etc.) that are produced or required at all stages of studying a cultural heritage object, collection or monument, or in the course of a conservation-restoration project. This includes resources and datasets that provide and enrich our knowledge and deepen our understanding of the creation, but more importantly the vulnerability or pathology and change over time of the materials or the appearance of the colour-bearing collections. It includes datasets and resources (observation notes, reports, drawings, photos, audio, video etc.) collected on the physical heritage objects, as well as datasets after various layers of processing, scientific analysis, interpretation and enrichment, what creates knowledge links/synapses and interact to enrich a cohesive and expanding knowledge graph.

The versioning feature allows for the enrichment or updating of records, as well as the integration of data generated or required at different stages of the workflow.

The development of the Repository as a custom instance of InvenioRDM has enabled the design of rich, domain-specific metadata schemas. These schemas have been adapted as needed to include relevant metadata sections and entry fields containing controlled lists to assist and facilitate users, and to simplify data ingestion. This allows for more accurate, comprehensive documentation and consistent descriptions of the data. At the same time, it categorizes digital assets more effectively, facilitating the search, discovery, retrieval and reuse of data.
All the data hosted in the Repository are available and accessible for immediate use and further processing by all stakeholders and target groups. All registered users are granted access to advanced search functionalities. Such versatile search and discovery capabilities (simple or advanced keyword search, custom filters, or advanced queries) enable users to efficiently locate and access the records they need, whether through simple keyword searches or more complex, subject-specific, and advanced queries.

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Access to data sources and reuse is not limited to the needs of documentation, conservation/preservation or management of the heritage objects but aims to broaden the horizons of perception, understanding, interaction and re-examination of the objects themselves, reviewing the role of colour in the aesthetics, meaning and value of the objects at the time of their conception and creation and throughout their subsequent course and evolution as cultural heritage objects.

In parallel, the provided REST API enables developers to search for and retrieve records programmatically. This is particularly useful in COLOURS for bidirectional communication between all COLOURS tools, enabling input data to be retrieved and output data to be stored after processing, as well as ensuring structural alignment, interoperability and integration of the repository with the broader ECCCH cloud ecosystem.

3.4 Simulation and predictive restoration Technologies (COLOURS Scenario 2)

The context for this scenario lies in the complexity of forecasting physical restoration processes, where historical fidelity, aesthetic coherence, and material preservation must all be carefully considered [***Arteaga et al. 2023***]. Traditional methods often fall short in providing experts with predictive capabilities to foresee the outcomes of their choices. This scenario addresses these gaps by improving/developing tools that empower stakeholders to simulate restoration outcomes, providing a clear forecast of the effects of different approaches. These simulations will support the assessment of colour, material properties, and the overall aesthetic and historical impact of potential restoration actions. An illustrative example is the restoration of the Sistine Chapel mural paintings, completed in 1994. The cleaning process revealed unexpectedly vibrant colours, previously obscured by grime and earlier restorations, which sparked significant controversy. Scholars and the public debated the fidelity of the results, as the transformation differed markedly from the subdued tones to which viewers had grown accustomed. This highlighted the need for tools that could simulate and visualize such outcomes beforehand, allowing scholars to evaluate their aesthetic

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and historical implications and facilitating dialogue among stakeholders before irreversible actions are undertaken.

In this scenario, the tools implemented will enable experts to virtually simulate the impact of restoration strategies on artifacts. For example, the vibrant colours revealed on a mural painting after cleaning can be modelled and visualised in advance, providing a clear understanding of how the restored artifact will appear. These simulations help assess whether the proposed method aligns with the artifact's historical authenticity and aesthetic coherence, ensuring that the selected restoration approach is both scientifically sound and culturally sensitive.

The focus of this scenario is to provide tools that not only forecast and simulate restoration strategies but also assist experts in choosing the most appropriate method. By documenting the entire decision-making process, these tools enable a clear rationale for selected actions while fostering consensus among interdisciplinary teams. This approach ensures that all interventions are thoroughly evaluated and justified before implementation, reducing risks and enhancing the quality and reliability of the restoration outcomes. This scenario directly addresses the challenges of balancing scientific accuracy, historical fidelity, and public perception in restoration projects. By providing robust predictive tools, it ensures that decisions are backed by data and visual evidence, facilitating informed, transparent, and collaborative restoration practices.

Based on the needs described above, the following requirements are proposed for tools supporting this scenario:

– The tool shall enable the visual simulation of the proposed conservation-restoration treatment (**virtual restoration**), predicting expected changes in colour, material properties and overall appearance before physical intervention takes place.

– The tool shall support comparison between alternative restoration approaches to inform expert decision-making.

– The tool shall document the rationale for selected restoration strategies, to support transparency and consensus among interdisciplinary teams.

– The tool shall provide outputs that can be shared with and understood by non-specialist stakeholders (e.g. curators, funders), to support dialogue before irreversible interventions.

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The specific stakeholder needs and corresponding functional requirements for this scenario regarding COLOURS digital tools are further detailed in Chapter 4.

3.5 Advanced Digital Tools for the Restoration and Conservation (COLOURS Scenario 3)

The context for this scenario lies in the complex and delicate nature of conserving and restoring artifacts, which often demands a careful balance between preserving authenticity and implementing necessary interventions. Many artifacts, such as mural paintings, polychrome sculptures, textiles, and historic photographs, require innovative approaches to address their specific vulnerabilities [***Derech et al. 2021***]. In cases like this, the use of digital twins, AI-driven analysis, and 3D modelling tools can provide a robust framework to guide and optimise restoration efforts [***Gigilashvili et al. 2023***]. Central to this scenario is the development of technologies that enable conservators to assess the condition of artifacts with high precision, simulate potential restoration strategies, and predict outcomes before implementing physical interventions [***Lermé et al. 2020***]. Digital twins of artifacts, augmented by real-time data collection and AI-based tools, allow for detailed visualisation of colour, texture, and material properties. These tools empower experts to conduct virtual experiments on the artifact's digital replica, testing various restoration techniques and evaluating their potential impact without compromising the artifact itself.

The tools implemented will not only support conservation-restoration processes but also provide comprehensive documentation of each intervention. This documentation ensures transparency and creates a valuable resource for future research and restoration work. By facilitating accurate analysis and minimising the risks associated with physical interventions, these technologies uphold the authenticity and material integrity of artifacts while optimising the efficiency and precision of restoration practices. For instance, in the case of a polychrome artifact, digital tools could assist conservators in reconstructing lost elements, simulating original colours, visualising and reassembling fragments virtually before any physical work is carried out like in the restoration project of the Madonna di Pietranico [***Arbace et al. 2013***]. This approach ensures that every step of the process is informed by data and visual evidence, reducing uncertainty and preserving the artifact's historical and aesthetic significance.

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This scenario emphasises the need for advanced digital tools to assist, document, and optimise physical restoration processes, with a particular focus on colour-sensitive artifacts. These tools are designed to address the challenges posed by both gradual degradations, such as pigment colour changes, and sudden damage caused by environmental events like floods or fires. By integrating cutting-edge technologies, the project aims at enhancing precision and minimising risks during restoration interventions, ensuring the historical and material integrity of cultural heritage items.

Based on the needs described above, the following requirements are proposed for tools supporting this scenario:

– The tool shall support the creation and management of the artifacts digital twin, integrating measured colour, texture, geometry and material property data acquired through calibrated imaging and analytical techniques.

– The tool shall enable conservators-restorers to assess and document the condition of objects with high precision, using visualisation and annotation functionalities. This will support the identification and mapping of original materials, later interventions and degradation phenomena.

– The tool shall support visualisation of lost or damaged elements (e.g. missing polychromy, fragments) and also virtually reconstructed areas prior to physical treatment, if foreseen.

- The tool shall adopt open standards and established models in the cultural heritage sector for data exchange and documentation, ensuring compatibility with existing conservation workflows and the long-term accessibility of the digital twin and its associated records.

- The tool shall provide conservators-restorers with reliable, measurement-based information and, if necessary, AI-assisted analysis to inform the planning of treatment, ensuring that each decision is supported by data and visual evidence.

– The tool shall generate comprehensive documentation of each intervention, to support transparency, traceability and future research.

The specific stakeholder needs and corresponding functional requirements for the COLOURS digital tools are further detailed in Chapter 4.

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3.6 Enhancing Public Engagement with Restored Colours through caring and authenticity experiences (COLOURS Scenario 4)

The context of this scenario addresses the challenges of anticipating public reactions to conservation-restoration outcomes and managing expectations, particularly when restored artifacts differ significantly from their pre-treatment appearance. Museum settings often struggle to present and interpret these artifacts in ways that fully communicate their historical and cultural relevance, especially when conservation-restoration processes are not transparently documented or when visual representations fail to capture their original vibrancy. This specific scenario is built on top of the results of the Caring Prototype designed and tested within the PERCEIVE project. This prototype has already defined a template, strategy, and approach that demonstrated to be particularly suited to enhance public understanding and trigger the sense of care towards the fragility of coloured artworks (**Veggi et al 2026**). A theory of care has been developed in the last years. The approach is based on a sequence of moments/experiences and technologies that support the cycle of caring.

1. SENSE OF WONDER AND SENSE OF LOSS. It starts from an introduction where visitors are confronted with the importance, sense of wonder of the heritage collection but also with the sense of loss when colours disappear;
    a. in this phase it is adopted emotional storytelling as a design strategy,
    b. the type of technology can change, although it is suggested to use an immersive, linear, non-interactive media (i.e. immersive video)
2. KNOWLEDGE GAP. The second step is meant to "close" the knowledge gap of the visitors and to provide historical information and description but also curiosity aspects, that are meant to keep the interest and attention.
    a. The strategy in this case is to adopt a simple and descriptive language
    b. The technology is not invasive (simple panels, audio and images, videos)
3. DEEPER KNOWLEDGE. In this phase, which is a continuation of the previous one, the visitor acts as a professional, as if she/he is directly called to action, unveiling /explaining at the same time the discoveries and their importance
    a. The strategy is to involve the visitors into an interactive application simulating the activity of the professional (i.e. a conservator making

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analysis on the pigments on a 3d copy of an object) and to strengthen the relation with the heritage;

b. Interactive Technologies are suggested in this phase, with a preference with tangible interaction, to create a better sense of embodiment

4. CARING: the last phase is meant to strengthen the caring attitude of the visitors by providing an award that shows that the results of their actions have consequences.
    a. The strategy here is to make the results of the restorers, conservators, scientists visible, together with the complexity of the work
    b. The suggested technology in this case should help to make visible the end results (such as the colour reconstruction), considering interaction to provide further details or information on the level of accuracy with the goal of disclosing the entire transparent process and empowering the visitors (i.e. Interactive Projection Mapping on an object or AR interactive visualisation)

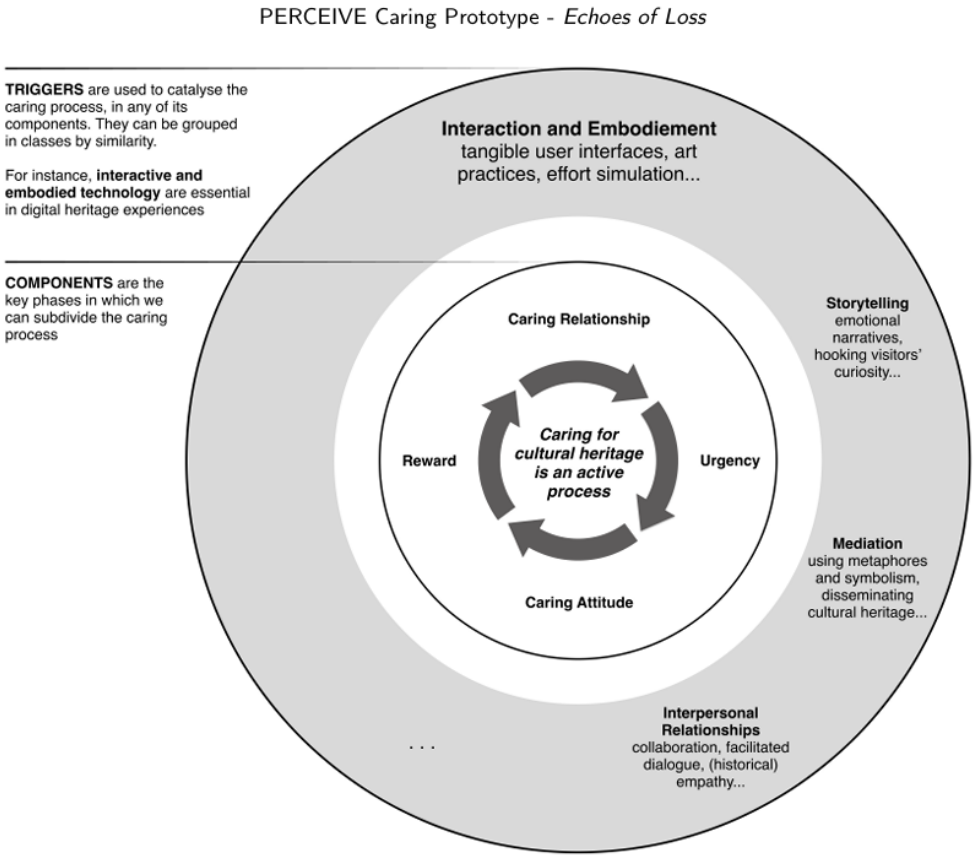


***Fig. 4**: The caring prototype strategy (from **Veggi et al 2026**)*

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This scenario envisions the use of a mix of technologies and storytelling techniques adapted to enhance how visitors can understand and enjoy collections and how improve how curators can exhibit restored artifacts. For instance, A relevant example is the Brancacci POV[8] project where augmented and mixed reality have been used to reimagine historical spaces and artworks, offering audiences an immersive and educational experience, considering the authenticity and caring dimension at the same time. By focusing on immersive and interactive visualisations, the project seeks to enhance public appreciation of cultural heritage and foster a deeper emotional connection to restored artifacts. Through these approaches, the public gains a better understanding of the original context and appearance of artifacts, transforming the way they connect with history and heritage and building a relation with our heritage.

This scenario therefore prioritizes the design and development of hybrid and XR technologies to provide audiences with an accurate interpretation of restored artifacts, fostering greater transparency and trust. By integrating digital solutions and caring prototype templates from PERCEIVE project and storytelling, the project redefines how restored cultural heritage is experienced, ensuring it resonates with contemporary audiences while preserving its historical integrity.

The following requirements are proposed for tools supporting this scenarioThe applications or digital solutions tool shall:

- enable intuitive comparison between the current, intermediate and reconstructed states of the artefact
- present multiple plausible reconstructions where appropriate, avoiding presenting a single one as definitive and explaining why interpretations differ.
- link reconstructed colours to diagnostic data, historical sources and expert observations, offering concise explanations.
- visually distinguish confirmed, probable, possible and speculative elements and explain gaps in the available evidence.
- integrate restored colours into digital narratives relating them to the artefact's context, use, symbolism and transformations over time.
- support adaptable experiences, such as web, mobile, large-screen and XR , adaptable to onsite (museums), remote and hybrid settings.

[8] http://brancaccipov.cnr.it

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- apply colour-management procedures to ensure consistent colour representation and communicate device-related limitations.
- provide simple, multilingual and accessible interfaces with different levels of interpretation for diverse audiences.
- explain the main stages of examination, reconstruction and decision-making, presenting restoration as an interpretative rather than mechanical process.
- allow visitors to compare options and preferences, eventually distinguishing public input from professional decisions.
- preserve traceability between public content and its sources, versions and authorship, without concealing uncertainties or disagreements.
- support the assessment of visitor understanding, engagement and trust through both quantitative and qualitative methods.

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4. Requirements for COLOURS Digital Tools

This section translates the stakeholder needs identified in Section 3 into a first set of functional requirements for the COLOURS digital tools, organized by tool.

To make this translation explicit, a distinction is made between stakeholder needs and functional requirements. A need expresses a problem, constraint, or expected form of support emerging from professional practice, while a functional requirement specifies a capability that a COLOURS tool or digital environment should provide in response to that need. This distinction helps maintain traceability between the originating workflow, stakeholder group, use case, and the resulting requirement.

On this basis, this chapter focuses on the requirements for the COLOURS digital tools as they pertain specifically to conservator-restorers, as the primary intended users. Conservation-restoration practices are governed by the principles of minimal intervention, reversibility, and evidence-based decision-making, which translate into a set of broader needs that precede any specific technical task and, consequently, condition the design of digital tools designed to support it. Prior to any physical intervention, practitioners require reliable means for the material characterization of objects— differentiating original materials from later additions and interventions, as well as identifying and monitoring degradation phenomena — and of anticipating the consequences of proposed treatments. These broader needs can be articulated along three axes: **non-invasive and non-destructive diagnostic methods and simulation capabilities**, to inform treatment planning prior to physical intervention; **objective, reproducible documentation** of condition and treatment history, supporting both internal decision-making and accountability to stakeholders such as funding bodies, museum boards, and related authorities; and the **mitigation of risk and reversibility constraints** associated with physical treatment, through prior virtual testing and validation of hypotheses.

4.1 User feedback on COLOURS tools

This section presents a synthesis of the needs and requirements identified by the community of conservators-restorers on the basis of the COLOURS digital tools'

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current state of development. The feedback was collected throughout the duration of WP2, including through dedicated engagement activities, such as the Ljubljana Workshop (May 2026), and reflects practitioners' assessment of the tools' relevance, usability and fitness for integration into current conservation-restoration workflows. Where a tool is at an early stage of development and was assessed through a preliminary or proof-of-concept demonstration, this is indicated explicitly, and the corresponding feedback is framed as validation and specification of requirements rather than as evaluation of a mature tool.
For each tool, a description of its current state and functional scope is followed by the analysis of needs and requirements emerging from stakeholder feedback. This analysis informs both the tool-level requirements formalized in the sections 4.1-4.5, as well as additional functionalities discussed in Section 5.1, ensuring that the resulting requirements comprehensively reflect the needs identified through stakeholder engagement.

Evolution of the toolset.

The tools assessed in this deliverable are those specified in D3.1 and integrated in the COLOURS Vertical Application (D7.1). The toolset has evolved since the Grant Agreement in three ways, none of which changes the project objectives. Some tools inherited from PERCEIVE have been merged or renamed. Two capabilities first planned as new functions of existing tools are being developed as stand-alone tools. VarnishLab, for the simulation of varnish removal and re-varnishing, responds to needs identified in the WP2 engagement activities and in the analysis of Pilot 1 (Section 4.1.5). Neg2Pos, for the conversion of colour negatives, responds to needs of photographic and film archives identified in the scouting activities of the early project phase (D3.1; Section 4.1.6).

Development of the Degreening Tool is limited to integration and validation, since the tool already covers its core use case. Table 2 links the names used in the Grant Agreement, in D3.1 and in this deliverable.

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Table 2: Correspondence between tool names in the Grant Agreement, D3.1 and this deliverable.

Grant Agreement	Current name (D7.1, D2.1)	Origin	Change
COLOURS Knowledge Repository	Colour Knowledge Repository (CKR)	PERCEIVE, extended	Extended for conservation-restoration data
ATON	ATON / Collaborative Simulation Environment (CSE)	Existing framework (CNR); CSE developed in WP4	CSE needs analysed in D2.2
MuLaX	MuLaX	PERCEIVE	—
Light damage estimator and Time Slider tool	LDE	PERCEIVE	Time Slider integrated
Deep de-greening tool	Degreening Tool	PERCEIVE	Integration and validation only
Kodacolor Colorizer	doLCE 2.0	PERCEIVE	Renamed
Semantic 3D atlas generator; Semantic 3D stylizer	StyleShade3D	PERCEIVE	Merged into one tool
(function of existing predictive tools; Pilot 1, T3.2)	VarnishLab	New	Stand-alone tool
- (not listed in the GA; within the scope of Objective 3 and Pilot 45)	Neg2Pos	New	Stand-alone tool
listed in the GA and confirmed after the online codesign workshops activities (D3.1)	CoDesign webApp Tool	PERCEIVE	Stand-alone tool

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4.1.1 Light Damage Estimator (LDE)

The Light Damage Estimator (LDE) is a web-based decision-support tool developed within the PERCEIVE project for predicting and visualising cumulative light-induced colour change in photosensitive cultural heritage materials, currently assessed at Technology Readiness Level 5 at project start, with a target of TRL 7 by the end of the project (see D3.1). Maintained solely by IESL-FORTH under a GPL-3.0 licence and implemented in Python as a modular API-based service, the tool supports conservators and collection managers in moving beyond generic illuminance-based guidelines toward object-specific, evidence-based lighting risk assessment. The underlying methodology follows the spectral photodegradation model of **Siozos et al. (2025)**, which characterises light sources across three spectral bands (Blue: 380-500 nm, Green: 500-600 nm, Red: 600-780 nm) and derives band-specific radiant exposures as inputs to empirically established photochemical kinetics equations. The pipeline proceeds from user-defined light source, intensity, and exposure duration inputs through band radiant exposure computation to predicted cumulative colour change expressed in CIELAB 1976, returned as interactive spatial visualisations and downloadable analytical reports. Stakeholder feedback indicates medium-to-high relevance of the LDE to conservation practice, with particular value identified for museum contexts in which exhibition planning and loan management require anticipating the light-sensitivity of pigments and dyes and subsequent photochemical degradation and alteration of appearance. Conservators-restorers identify a need for the tool's outputs to support decision-making in retouching material selection, risk assessment, and preventive conservation planning, as well as to provide virtual representations of an object's plausible past or future chromatic states in support of both treatment planning and scientific research.

With respect to the tool's interface and output design, a need has been expressed for the visualization of colour-coordinate shifts within a three-dimensional CIELab space, rather than the current representation, to improve interpretability of results.

A further need expressed concerns the extension of the tool's analytical scope to manuscripts and photosensitive inks, currently outside its coverage. Among the functionalities considered priorities for further development, the capacity to

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reconstruct an object's original appearance prior to photochemical degradation — effectively complementing the tool's current forward-projective logic with a retrospective one — is the most strongly emphasized.

Finally, one recommendation for future development is to simplify input data requirements: VIS-NIR hyperspectral imaging and XRF mapping, currently employed by the tool, are not commonly acquired within standard conservation-restoration workflows. Aligning the tool's data requirements with data commonly generated during standard practices is accordingly identified as a priority for the tool's future development. Any simplification of the input data, however, will need to be weighed against its potential impact on output accuracy.

These needs are consistent with, and substantially informed by, the end-user evaluation of the LDE conducted within the predecessor project PERCEIVE (Deliverable D7.2), which involved a targeted campaign among conservation professionals and researchers (N=24), the majority with prior knowledge of conservation and diagnostic analysis in cultural heritage.

Respondents reported the following quantitative results:

- Interface aesthetics: mean 4.33/5, 91.7% positive
- Intuitive usability: mean 4.04/5, 83.3% positive
- Processing speed: mean 3.33/5, 37.5% positive, with most responses neutral rather than positive, identifying this as the principal usability weakness
- Perceived usefulness: 66.7% considered the tool useful either in its current form or following modification, while a further third rated it not yet useful, indicating that adoption is conditional on further development rather than reflecting a lack of relevance

Recurring qualitative feedback converged on the following priority areas, which directly inform the present requirements:

- Incorporation of additional degradation factors, including humidity and air pollutants, and extension beyond controlled display environments to outdoor exposure scenarios
- Broader coverage of artworks and materials, together with the ability for users to upload their own images or datasets

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- Improved inspection and output reporting, including zoom functionality, higher effective image resolution, and quantitative indicators of predicted colour change
- Interest in an inverse simulation workflow, whereby a currently faded artefact could be used to hypothesise its original appearance, corroborating the retrospective reconstruction capability identified as a priority in the present analysis

Finally, the absence of empirical ground truth for validating the realism and accuracy of predicted colour change was raised as a factor affecting user confidence in the tool's outputs, underscoring the importance of transparent communication of assumptions and limitations in future development of the LDE.

4.1.2 ATON framework & MuLaX

ATON is an open-source Web3D/WebXR framework to present and interact with complex and/or multi-dimensional data on the web [Fanini et al. 2021]. It also allows to build interactive Web3D/WebXR applications accessible directly via common web browsers, without any installation required for final users.
ATON supports high-performance, responsive 3D visualization and real-time collaboration. It offers functionalities for 3D scene management and editing, semantic annotations, measurements, lighting and materials, synchronous and asynchronous collaboration (crucial for the design and implementation of collaborative simulation environment), and spatial user interfaces for XR sessions.
ATON has a built-in front-end ("Hathor") offering advanced functionalities (for general purpose presentations in CH) and an editor profile to create and arrange a 3D scene with ease.
The framework also offers a plug & play model to accelerate the creation and deployment of vertical applications built on top of ATON features (see D3.1).

Thanks to its involvement in several past national and international projects [**Fanini et al. 2025**], its involvement in a few other ECCCH sister projects, and the complete redesign of UI blueprints offered [**Amadei et al. 2025**], the framework, assessed at TRL 7 at project start, is progressing towards the TRL 8 target set for the end of the project (see D3.1).

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MuLaX [**Fanini et al. 2025**] is a Web3D tool developed in PERCEIVE and built on top of ATON, through the plug&play model. It enables the online exploration of multi-layered 3D cultural heritage collections alongside the inspection of diagnostic and analytical data processes. The tool supports advanced multi-layer discovery techniques, POIs (point of interest), texture-based masks, and interactive semantic painting. Through ATON it is accessible directly via web browser on any device, from smartphones to immersive XR headsets, ensuring wide interoperability. By integrating analytical datasets into spatially referenced 3D environments, MuLaX facilitates documentation, monitoring, interpretation, and communication of diagnostic processes for both experts and broader audiences (see D3.1).
The TRL of MuLaX in COLOURS starts from 6, targeting 7 at the end of the project.

The MuLaX Web3D tool and the underlying ATON framework are identified as tools of high relevance for linking material analysis results to conservation-restoration practice through interactive, integrated visualization of diagnostic data. Stakeholders highlight the need for the tools' support towards a structured organization of research outputs, the holistic interpretation of multi-layered examination results, and the production of clearer, more structured conservation-restoration documentation (conservation-restoration report). With respect to reporting functionalities, a requirement is identified for the direct generation of exportable documentation of visualisation snapshots that have been tailored, along with respective annotations included in a study or session — as well as for more detailed and customizable documentation options. A further requirement concerns the simultaneous display of multiple categories of analytical data from a variety of acquisition techniques (e.g. outputs from different spectroscopic techniques) referenced to the same spatial location on an object, rather than requiring separate consultation of each dataset. The principal constraint identified relates to the effort required for data preparation and formatting prior to import; streamlining data ingestion procedures is accordingly identified as a priority requirement for future development.

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4.1.3 StyleShade3D

StyleShade3D, developed in PERCEIVE, merges with the Semantic 3D Atlas Generator and the Semantic 3D Stylizer foreseen in the Grant Agreement (D3.1). Assessed at TRL 4 at project start (see D3.1), it has since advanced to TRL 5 (technology validated in a relevant environment). This assessment reflects the availability of a fully integrated and functional prototype that has been tested on eight representative cultural-heritage objects with diverse geometries and surface characteristics. The system has not yet undergone a controlled end-user study or been demonstrated as part of routine professional production; therefore, a higher classification such as TRL 6 would currently be difficult to justify. The complete pipeline can be launched with a single command and is shown below. From left to right it takes a 3D model with a valid, non-overlapping UV map as input and automatically selects a compact set of camera views that covers the model's sampled surface. This is achieved by formulating viewpoint selection as a set-cover problem and applying a greedy optimization strategy. The selected views are then rendered and provided through a fully functional interactive user interface. Within the interface, users define and refine the desired model regions. The SAM 2 vision foundation model assists by predicting segmentation masks from user prompts, while users retain control over segment boundaries and semantics. This human-in-the-loop approach supports application-specific segmentation and enables the correction of incomplete or inaccurate predictions. After annotation, the pipeline automatically back-projects the masks from all rendered views onto the model's UV parameterization and combines them into a unified segmented atlas. This atlas can directly support downstream workflows such as segment-wise material assignment, shading, style transfer, texture editing, and semantic labelling.

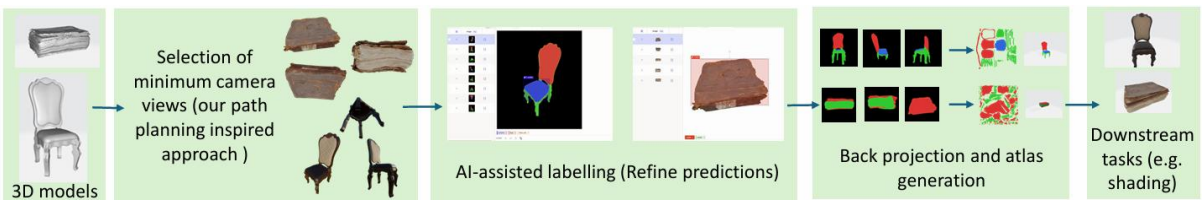


***Fig. 5**: StyleShade3D Pipeline*

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Stakeholder engagement with this tool has to date been more limited compared to the other tools discussed in this section, and the corresponding evidence base is accordingly narrower. Indirect evidence comes from current practice: Some professional, according to the result of the discussion made during the workshop in Ljubljana, uses general-purpose image-editing software to simulate colour variants of façades and interiors, test visual solutions before intervention and communicate them to investors (Section 2.2.1). The pilot case studies on paintings also require the restoration of original colours on 2D images, using diagnostic data to identify overpaints and degraded pigments. Relevance has been identified with regards to the employment of the tool for the simulation of different conservation-restoration approaches or scenarios, e.g. neutral retouching, which refers to the careful inpainting of areas where original paint has been lost or damaged, in a way that does not alter or compete with the perception of the original artwork, as well as for the interdisciplinary collaboration with scientists, curators, and other stakeholders, and monitoring and preventive conservation planning.

The tool generates an interpretable, colour-coded segmentation atlas for material assignment, shading, and semantic labelling. It requires a 3D model with a valid, non-overlapping UV map. Complex geometries, cavities, fine structures, and weak visual boundaries may require manual correction. Planned improvements include better editing tools for small regions, improved viewpoint selection, fewer projection artefacts, and greater automation through task-specific model adaptation.

4.1.4 Colour Knowledge Repository (CKR)

The Colour Knowledge Repository (CKR) is being expanded to meet the needs and requirements identified by our community of conservators-restorers, and comply with the technical frameworks of both the ECHOES-ECCCH platform and the Heritage Digital Twin Ontology (HDTO).

The Technology Readiness Level (TRL) was assessed as 7 at the start of the project. It will be 8 by the end of the project, demonstrating and validating the CKR integration within COLOURS VA, as well the ECCCH Knowledge base (for more

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details, see D.3.1 and D7.1). The latest version of the CKR is already available here: https://colours-repository.iesl.forth.gr

Additional functionalities implemented to date, based on the above needs and requirements, include the following:

- Based on our users' activities, two **Communities** were created: "Digital restoration of colours on paintings" and "Conservation workflows".
- Several additional **resource types** were added, addressing conservation-restoration datasets (from 61 to 71 resource types) e.g. Dataset / Multispectral Imaging, Image / White Light (or Visible light) Photography, Workflow / Modeling, Report / Condition report, Physical Object etc.
- The **controlled vocabularies/dropdown lists** were enriched for cultural heritage objects and restoration provenance. More specifically, the controlled lists for Research focus, Research Activity Type and Technique.
- A "**Physical Object Description (Heritage entity)**" section was added to the record upload form. This section is visible only if the user selects Physical Object as a resource type. It includes some required fields (like the "Physical object creator") and several optional fields (like Identification number, Object category, Dimensions, material, current location, ownership, valuation etc.)
- Every CKR record must **refer to a specific physical object** (Heritage object) selected from the list of existing objects (see the "Research Focus" section). This list is dynamically generated by the system. Therefore, a physical object record **must be created first** before uploading any other type of record that refers to this heritage object.
- Any user can **save custom metadata templates** and reuse them at any time during the upload of a record.
- User Interface **improvements** like statistics (views & downloads for every record and version), preview of audio & video files, administrator dashboard, submission of a record to multiple communities after its creation, optimized Community management (for records & members).

Some planned enhancements include the following:

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- Apart from diagnostic analytical data (e.g., UV luminescence, visible-induced luminescence, XRF, spectroscopy, high-resolution 2D images, and 3D models), other multimodal assets will be stored e.g. conservation reports.
- Expose the CKR API to dynamically exchange data/metadata with external tools (such as ATON and MuLaX) and ensure interoperability with the ECCCH cloud infrastructure.
- ORCID-based accounts are currently used, but access to ECCCH services requires the federated trust model and the common OAuth2/OpenID-based access-control approach (integration with the ECCCH AAI/SSO infrastructure). ECCCH-level roles and rights access will be resolved.
- The CKR will publish and enrich HDTs to the ECCCH based on the stored physical objects and metadata records.
- Semantic Discovery & Querying. We plan to enable deep semantic query execution based on a mapping to the HDTO (CIDOC-CRM extension) and the integration with the ECCCH platform.

The COLOURS platform and CKR will be deployed as a provider-operated Vertical Application to the ECCCH. The weak points of current research listed at the Ljubljana workshop, such as the lack of comparative material, poorly documented past interventions and data stored in different formats and systems (Section 2.2.1), are the needs the CKR addresses by linking every record to its physical object and supporting versioned, structured documentation.

4.1.5 VarnishLab (Tool under Development)

Unlike the tools previously discussed in this section, the VarnishLab is not inherited from PERCEIVE and was assessed at an early stage of development. The underlying functionality is, however, anticipated in the DoA. The simulation of varnish removal is explicitly listed among the restoration scenarios to be tested in Pilot 1, whose first research question concerns the removal of non-original varnish. It also falls within the scope of Objective 2 and Task 3.2 (prediction and simulation of colour change, including discolouration). In the original work plan, this capability was expected to be delivered as a predictive functionality of existing tools rather than a stand-alone tool. The early stakeholder engagement activities of WP2 and the analysis of the Pilot 1 case study pointed to a need exceeding the

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scope of such an extension, in particular regarding the simulation of re-varnishing, which is largely unaddressed by existing approaches. The functionality was therefore specified as a dedicated, physics-based tool in D3.1, where it is assessed at TRL 3 at project start, with a target of TRL 6 by the end of the project. A preliminary proof-of-concept was then presented at the Ljubljana Workshop (see Section 2.2.1), where the need for a painting-oriented cleaning simulation also emerged independently from the group work (Section 2.2.2, Annex 2b).

The feedback reported below is therefore framed as validation and further specification of the tool's requirements, rather than as the evaluation of a mature tool.

VarnishLab should be distinguished from the optional varnish module foreseen within the Light Damage Estimator (see D3.1). In the LDE, the varnish layer is modelled as a wavelength-dependent filter and as a contributor to the overall perceived colour shift, in order to improve the prediction of light-induced colour change in varnished paintings within a preventive conservation context. VarnishLab addresses instead the interventive stage: it simulates the appearance of a painting following the removal of aged varnish and the application of a new varnish, to support treatment decisions prior to irreversible intervention. The two components are therefore complementary and do not overlap in scope. Where appropriate, they may share varnish characterisation data, such as the optical properties of varnish types derived from mock-ups.

Stakeholders assessed the functionality as highly relevant for painting conservator-restorers, identifying its core value in simulating the appearance of an artwork following varnish removal and, separately, following revarnishing, in support of treatment proposals, risk assessment, and communication with scientists, curators, and other stakeholders prior to irreversible intervention. A specific need identified is the provision of a before/after comparison mechanism (e.g. a slider interface, similar to the LDE) enabling immediate visual assessment of simulated outcomes. Additional needs identified include the incorporation of spectral measurements from coloured — rather than exclusively achromatic — regions of the artwork, to reduce residual discrepancies between physically and virtually cleaned states, and the provision of output imagery at higher resolution.

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As with other simulation-oriented tools discussed in this section, future development suggests the simplification of input data requirements: stakeholders indicated that the functionality should operate on calibrated RGB imagery and point spectral measurements, given the limited availability of hyperspectral data within standard workflows. However, consistent with the point raised earlier, any simplification of the input data may compromise the accuracy of the tool's output. It is further noted that the definition of a "cleaned reference" state is inherently dependent on the cleaning methodology applied as well as the visual perception of the professional, a methodological consideration to be accounted for in the future specification and validation of this functionality.

4.1.6 Neg2Pos

Like VarnishLab, Neg2Pos is not inherited from PERCEIVE and was assessed at an early stage of development: TRL 2 at project start, with a target of TRL 6 (D3.1). Its scope is anchored in the Grant Agreement, which lists historic photographs and films among the materials addressed by Objective 3 and Scenario 3, and devotes 4 to historical photographic and film materials. The need for the tool emerged from the scouting activities of the early project phase (D3.1), which for this tool consisted of a review of archival practice and of the literature by its developers. The WP2 workshops did not involve film and photographic archives (Section 2.3), so the tool has not yet been discussed with its end users.

Commercial inversion software and digital intermediate workflows already support the scanning and colour correction of negatives. Less support exists for reproducing the tonal and colour characteristics of analogue prints and film projection, which matters when archives need historically informed renderings rather than corrected images (D3.1). This is the gap Neg2Pos addresses.

The tool was not demonstrated at the Ljubljana workshop, and photographic and film materials are not yet represented in the WP2 evidence base. Feedback will be collected from archives and film restoration professionals in 4 and in the external pilots. The requirements in Section 4.3.6 therefore specify the intended functionality and will be validated as development progresses.

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4.1.7 doLCE 2.0

doLCE 2.0, developed in PERCEIVE, reconstructs the colour information encoded in early lenticular films, such as Kodacolor, from monochrome scans (D3.1). It corresponds to the Kodacolor Colorizer of the Grant Agreement and is assessed at TRL 5, with a target of TRL 7. Film archivists, conservators and collectors need an accessible way to recover this information that copes with variations in scan quality and film condition and lets experts inspect and correct the reconstruction without programming skills (Pfluger et al. 2022; Sinha et al. 2026; Byrne et al. 2021). The human-in-the-loop approach developed in PERCEIVE responds to this need and is the basis for further development in COLOURS (https://lenticularfilmhitl.github.io/). The tool was not demonstrated at the Ljubljana workshop, and film materials are not yet represented in the WP2 evidence base; feedback will be collected in Pilot 4

4.1.8 Degreening Tool

The Degreening Tool, inherited from PERCEIVE, removes greening defects from digitised Autochrome plates with a deep-learning model trained on synthetic defects (D3.1). The Grant Agreement lists it among the tools of Scenario 3 (TRL 5 to 7) and applies it in Pilot 4. The tool already covers its core use case. It detects greening areas reliably enough to leave only limited manual post-processing, which takes much less time than a fully manual correction with general-purpose image-editing software (D3.1). The WP2 activities of the first year did not identify new functional needs for it, partly because they focused on paintings and polychrome sculptures.

No further algorithmic development is therefore planned, in line with D3.1. Development effort is directed instead to VarnishLab and Neg2Pos, which address needs only partly covered by existing solutions (Sections 4.1.5 and 4.1.6). The Degreening Tool remains part of the COLOURS toolset: it is integrated in the COLOURS Vertical Application as a platform-managed service that stores its outputs in the CKR (D7.1), it will be validated with conservation professionals in the pilots, and it will be documented for photographic archives and conservation laboratories. These activities are expected to bring it to TRL 7. Should the pilots

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reveal functional gaps, a targeted enhancement will be considered, as foreseen in D3.1.

4.1.9 CoDesign Tool

The CoDesign Tool, developed by CNR ISPC and Fraunhofer IGD in PERCEIVE, is a card-based framework for the participatory design of visitor experiences (Travaglini et al 2025). It exists as a paper board game and as a concept for a web application under development (D3.1). It was included in the list of potential tools that could support COLOURS impact (Table 2.2.6 Business Model of G.A.) and it was confirmed after the early scouting and engagement activities showed its value for colour-driven exhibition design and participatory heritage practice (D3.1). It was required for the early codesign activities in WP2.

Since an online version (webApp) was not available as a Beta (only the paper version was available and robust but not useful for remote activities), during WP2 codesign online workshops, we needed to use an adapted version of the paper version made with Miro platform (Section 2.2.2, Annex 2b). This exercise served specifically to highlight the value of the tool and a requirement for an online version, aligned with COLOURS specific needs. The sessions in fact showed that the tool helps interdisciplinary groups combine COLOURS tools into end-to-end workflows and makes missing functionalities visible when a storyboard cannot be supported by the current toolset. They also pointed to two needs: **a clearer definition of tool chains within the design process, and a shorter, more brainstorming-oriented ideation phase**. A round-based ideation extension with tool cards and use-case scenarios has been designed in response and tested online. The Miro online version highlighted also some limitations that have been considered in the development of the CoDesign WebApp. The professionals stated that they would need an in-person validation, showing a low trustability that we expect to overcome in the Colour CoDesign WebApp (D3.1).

4.1.10 Transversal needs

Beyond the tool-specific needs outlined above, two requirements recur consistently across the tools, and emerging concepts assessed and warrant

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particular attention in the definition of the requirements presented in the following sections. First, a structural misalignment is identified between the input data required by the majority of the tools — notably hyperspectral imaging — and the diagnostic data routinely generated within standard conservation-restoration workflows; addressing this misalignment, whether through adapted data requirements or through guidance on data acquisition, constitutes a cross-cutting requirement for the toolset as a whole. Second, a need for increased automation is identified across tools, particularly with respect to automated documentation and reporting and the integration of AI-assisted functionalities, reflecting stakeholder expectations shaped in part by comparison with established commercial image-editing solutions.

The presentations of the conservator-restorer partners confirm this misalignment: routine documentation relies on visible, raking-light, UV fluorescence and near-infrared photography and on microscopy, while XRF and Raman spectroscopy are carried out on request by external specialists (Section 2.2.1). A further practical constraint concerns field work, where electricity and internet connection may be lacking.

4.2 Mapping of Stakeholders needs with the Associated COLOURS Tools & Functions

The tables below translate these broader needs into specific application-level requirements for COLOURS digital tools, as articulated across the project's internal pilots, in collaboration with their associated stakeholders. An Internal-Pilot-centered analysis will follow within the framework of WP10.

As mentioned, these needs come from the workflow analysis carried out with the conservator-restorer partners of the internal pilots (Section 3.2), from the Ljubljana workshop and survey (Annex 2a) and from the online co-design workshops on Pilots 1a and 2a, b (Annex 2b); the source is indicated where a need does not come from the workflow analysis. Since these activities concerned paintings and polychrome sculptures, Table 3 does not yet cover photographic and film materials. The needs and requirements for the tools that address them, Neg2Pos, doLCE 2.0 and the Degreening Tool, are discussed in Sections 4.1.6–4.1.8 and will be verified in Pilot 4 and/or external Pilots.

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Table 3: *Identified Needs, Target Applications, and Associated Digital Tools*

Identified Need(s)	Identified Targeted Application	Description of specific applications	Associated COLOURS Tools & Functions
Accurate interpretation of multi-modal diagnostic data to inform treatment decisions/ Shared open-access data repository	Visualization of diagnostic data for the identification of non-original material and degradation areas	Collective visualization of data, enabling further interpretation.	MuLaX, CKR, CSE
Precise, evidence-based area-mapping (overpaintings, interventions, varnished/waxed, degradation)	Mapping/ masking of overpainted/ degraded/ varnished or waxed areas	Localization of original polychromy residues, mapping of areas containing non-original material, areas affected by degradation phenomena in an evidence-based, semi-automated manner	StyleShade3D, MuLaX
Testing and validation of conservation-restoration hypotheses prior to irreversible physical treatment.	Virtual removal of overpainted areas and old retouches & simulation of neutral retouching	Assessment of the outcomes of future conservation treatment(s)	StyleShade3D
Anticipating treatment outcomes prior to irreversible physical cleaning	Algorithmic wax removal/ Digital varnish removal and revarnishing		VarnishLab
Evidence-based, reproducible reconstruction of original appearance to support conservation-restoration decisions and communication with stakeholders	Virtual restoration or reconstruction of original appearance	• Assessment, hypothetical reconstruction and visual representation of the original appearance of the pictorial surface based on a synthesis of available data. • Assessment and hypothetical reconstruction of variations in the object's format • Virtual recontextualization of dispersed objects within their original ensemble	StyleShade3D

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Anticipating light-induced colour change of sensitive materials	Prediction of colour change under defined lighting conditions	Lighting choices and risk assessment for exhibitions and loans; monitoring and preventive conservation planning (Section 4.1.1, Annex 2a)	LDE
Communicating conservation decisions and their uncertainty to the public	Public-facing visualisation of reconstructions and of the conservation process	Contextual or AR visualisation of alternative reconstructions; visitor-facing explanations of uncertainty; public formats derived from the professional workflow (Annex 2b)	CSE, StyleShade3D

4.3 Functional Requirements for the COLOURS digital tools

This section sets out the functional requirements for the COLOURS tools included in the preceding analysis. The requirements are a result of the analysis of user feedback presented in Section 4.1 and the association of tools with the applications identified in Section 4.2. As explained in Section 5.1, the feasibility of each requirement will be verified on the internal pilots before any adaptation or extension is specified.

Regarding sections 4.3.6, 4.3.7, the COLOURS tools Neg2Pos and doLCE 2.0 were not included in the previous analyses of stakeholder needs, since the participants in the analysis mentioned in the previous chapter are not professionals working on photographic film archives. The requirements for these two tools were therefore defined by the developers of the tools based on the scientific literature, established archival practice and the results of previous research (including the PERCEIVE project for doLCE). They will be validated and refined through feedback from film archivists and practitioners during pilot testing.

4.3.1 MuLaX and the ATON framework

MuLaX shall allow the simultaneous display of multimodal data, referenced to the geometry of 2D or 3D objects. This will enable the simultaneous examination and interpretation of data, rather than their examination as separate datasets. The tool shall also import segmentation maps produced by StyleShade3D as labelled, spatially referenced layers.

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The tool shall provide streamlined data ingestion, supporting common instrument output formats through a guided import procedure, with automatic format validation and conversion. Research outputs shall be organised in a structured way. For documentation, MuLaX shall generate exportable PDF reports directly from the 3D environment, including annotations, points of interest and linked analytical data.
Where these reports are used as condition reports, their structure and content shall follow the essential contents of the European standard EN 16095:2012 (Conservation of cultural property – Condition recording for movable cultural heritage), to ensure consistency and comparability with established conservation documentation practice.

4.3.2 CKR

As the CKR is designed to host all the digital resources retrieved for deploying all the other COLOURS tools, the identified improvement needs were translated into functional requirements and implemented in the early stages of the project. This implementation was necessary to finalise the CKR upgrade and release, enabling users to upload all the data for the internal pilots. Therefore, several user-led improvements and additional functionalities have already been implemented, as described in Section 4.1.4. The planned enhancements listed in Section 4.1.4 constitute the remaining requirements for the CKR: the storage of further multimodal assets, including conservation and condition reports; an API for the dynamic exchange of data and metadata with the other COLOURS tools; access through the ECCCH authentication and authorisation infrastructure; the publication of Heritage Digital Twins to the ECCCH; and semantic querying based on the mapping to the HDTO (D7.1). Since workshop participants considered a full day of practical training necessary (Annex 2a), guidance for first use should also be provided.

4.3.3 StyleShade 3D

StyleShade3D provide semi-automated, data-driven (and/or AI-assisted where appropriate) segmentation of areas of interest, permitting the user to maintain control over segment boundaries and category labels, such as overpaint,

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retouching, varnish or wax, degradation, and residues of original polychromy. To ensure evidence-based mapping rather than segmentation determined by visual appearance alone, the tool shall accept diagnostic data layers, such as XRF maps, as a guide for segmentation. It shall record, for each mapped area, the evidence on which it is based. The segmentation workflow shall include precise editing tools for small regions, fine structures, cavities and weak visual boundaries.

For the reconstruction of original appearance or the simulation of different conservation-restoration hypotheses (e.g. neutral retouching), the tool shall generate hypothetical reconstructions for each segmented area, based on diagnostic evidence such as pigment identification, and shall support several alternative hypotheses for the same object. Alternative scenarios shall be comparable side by side against the current state of the object. All simulations shall be implemented as non-destructive, reversible layers that can be saved, documented and shared with researchers, curators and other stakeholders. Each reconstruction shall document its sources and assumptions so that it can be reproduced and shall clearly distinguish surviving original material from reconstructed areas. Reconstructions shall be exportable as visual representations suitable for communication with non-specialist stakeholders.

4.3.4 Light Damage Estimator (LDE)

The LDE shall work with input data commonly acquired in conservation practice, such as calibrated RGB images and point spectral measurements, and shall state how reduced input affects the accuracy of predictions. To improve accuracy on complex colour compositions, such as pigment mixtures or varnished surfaces, hyperspectral data shall be accepted as an optional input in addition to calibrated RGB images, where available. The LDE shall present predicted colour change in quantitative and visual form, including a three-dimensional CIELAB view, allow users to upload their own data and make the assumptions and limits of each prediction explicit. The simulation of the appearance before degradation and the extension to further materials and degradation factors are candidate requirements (Section 5.1).

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4.3.5 VarnishLab

VarnishLab shall simulate two successive stages of a varnish treatment: the removal of an aged, discoloured varnish, and the application of a new varnish layer. Conservator-restorer professionals specializing on paintings need to assess the likely visual consequences of removing aged varnish or applying a new coating before undertaking physical treatment. Research on varnish appearance and virtual cleaning supports the value of computational previews for exploring changes in colour and contrast and informing treatment decisions (Berns and de la Rie, 2003; Trumpy et al., 2015; Maali Amiri and Messinger, 2021).

Proposed requirements include importing RGB images and hyperspectral data; adjusting the degree of varnish removal, new varnish thickness and surface properties; and applying simulations to selected areas. Side-by-side views should compare the untreated, virtually cleaned and re-varnished painting, complemented by spectral reflectance curves where available. Exported results should document simulation parameters and material assumptions so that conservators can interpret and reproduce each preview.

As the tool was assessed through a preliminary proof-of-concept, these requirements will be refined through conservator feedback and pilot testing, focusing on visual reliability, ease of use and usefulness in treatment planning, and are to be validated as development progresses.

4.3.6 Neg2Pos

Film and photography archives need reliable ways to convert digitised colour negatives into positive images that reproduce the colour and tonal characteristics of analogue prints and projected film. This remains an expertise-intensive step: grading requires skilled personnel, while providing digital access to negative collections presents practical and interpretative challenges (**FIAF Technical Commission, 2012; Memory et al., 2026**). Historically informed rendering should preserve the material's aesthetic characteristics and retain expert control over colour decisions (**Byrne et al., 2021**).

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Proposed requirements include high-bit-depth image import, batch processing, capture-system calibration and specification of negative and positive materials. Users should be able to adjust printing exposure and colour filtration, compare results with reference images and simulate photographic printing or cinema projection, building on photochemical printing models (**Trumpy and Anderson, 2025**). Exported images should retain captured metadata, material specifications and processing settings to support transparent and reproducible workflows.
These requirements will be refined through archive and practitioner feedback, focusing on colour and tonal fidelity, consistency, ease of use and reduction of manual effort.

4.3.7 doLCE 2.0

Film archivists, conservators and collectors need an accessible way to recover the colour information encoded in historical lenticular films, such as Kodacolor, from monochrome scans. The workflow should accommodate variations in scan quality and film conditions while allowing experts to inspect and correct the reconstruction without requiring programming expertise (**Pfluger et al. 2022; Sinha et al. 2026; Byrne et al. 2021**). A human-in-the-loop approach was developed within the preceding PERCEIVE project and provides the foundation for the further development of doLCE 2.0 in COLOURS. The framework is presented on the project website - https://lenticularfilmhitl.github.io/.
Priority requirements are a guided workflow for importing scans, detecting lenticular boundaries, previewing reconstructed colours and exporting results; an interactive boundary editor; and simplified model fine-tuning using user-corrected frames. Batch processing, dataset management and the ability to save and resume training are also needed to support efficient work on film sequences. Outputs should retain processing settings and calibration information so that reconstruction decisions can be documented and reproduced.
These requirements will be refined and prioritised through pilot testing, focusing on ease of use, reconstruction consistency and reduction of manual effort.

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4.3.8 Degreening Tool

No new functional requirements emerged from WP2 for this tool (Section 4.1.8). It shall be available within the COLOURS Vertical Application.

4.3.9 CoDesign Tool

The CoDesign Tool shall support the definition of ideation and identification of use cases and toolchains through a round-based ideation stage with COLOURS tool cards, and a web version shall support remote and hybrid sessions (Annex 2b, D3.1). The ideation phase should support the use of Colours' Tools. As a result, it is expected that professionals can discuss and select ideas for digital projects aimed at simulating and communicating interactively coloured collections and their stories. Virtual / Hybrid Exhibitions *Concept and User Experience* will be defined at the end of the process as a pre-requisite of the prototype design and development.

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5. Prioritisation of Stakeholder Requirements

The requirements identified in Section 4 will be prioritised in collaboration with the working groups for each scenario, against three criteria: relevance to conservator-restorer workflows, technical feasibility within the project timeframe, and potential impact on conservation-restoration practice. The engagement activities already give indications of relevance and impact: the survey shows which tools participants considered most useful (Annex 2a), Section 4.1 reports the needs that stakeholders emphasised most strongly, and Section 5.1 distinguishes the functionalities considered fundamental from candidate requirements. Feasibility cannot be judged yet: it depends both on the current capabilities of each tool and on the type and quality of the data available for each case study (Section 5.1). Priorities set before this check would rest mainly on stakeholder preference and could favour requirements that the available data do not support.

Prioritisation will therefore take place after the feasibility of each requirement has been assessed on the internal pilots, combining these indications with the feasibility results. This assessment is carried out jointly by WP2 and WP10, using the data available for each case study. Each requirement will then be classified with the MoSCoW scheme (MUST, SHOULD, COULD, WON'T for this iteration) against the three criteria above. The resulting prioritisation will be reported in D10.2 (Internal Pilot Evaluation and Refinement Report, M24), with reference to the requirements of Section 4.3.

D2.2 assigns indicative priorities to the requirements of the collaborative environment, whose specification in D4.1 (M14) needs an earlier input. The tools addressed here already exist at different levels of maturity, and the deciding factor for their priorities is feasibility on real case-study data.

5.1 Stakeholder-oriented adaptation of COLOURS digital tools: Extensions and Additional Functional Requirements

The feedback collected from stakeholders indicates that the needs and requirements described in Sections 4.2 and 4.3, respectively, form a basis for the further development of COLOURS digital tools. However, any suggested adaptations or extensions should be supported by available data, and the case studies included in the internal pilots will form a test bed to finalise the

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formalisation of the input data required for the implementation of any suggested improvements. This will serve as a feasibility test for the proposed additional functionalities. The results of this feasibility study will in turn determine the prioritisation of the requirements, so that development efforts are first oriented towards functionalities indicated as achievable and most beneficial by the internal pilots' available data.

Once this has been passed, the next step will be to test, evaluate and validate the tools against user requirements. Some functionalities may be achievable with the tools in their current state or with minor adjustments. Others may require substantial development or may fall outside the scope of the tools altogether. The additional requirements outlined below should therefore be regarded as candidate development requirements to be confirmed, refined, or discarded in light of pilot testing, while their relative priority will be established on the basis of the feasibility study performed on the internal pilots trials. Regarding the LDE tool, the virtual representation of past states of the object, including its original appearance prior to photochemical degradation, cannot be performed at its present stage of development, as the tool currently predicts the objects' future states.

Evidence-based area mapping, namely the segmentation of the object on the basis of diagnostic data indicating the presence of different materials, is not currently supported by StyleShade3D. This functionality is considered a fundamental requirement, as the reliability of the virtual interventions described below depends upon the accurate segmentation of the areas concerned.

The virtual removal of overpainted areas and intervention materials is likewise not yet supported, and requires further investigation, with particular reference to the manner in which the underlying surface is to be represented. The simulation of neutral retouching may be attempted by means of StyleShade3D; however, further development is required for the tool to produce results of sufficient realism and offer the users the ability to select among retouching modes, to better inform conservation-restoration decisions. Algorithmic wax removal and digital varnish removal constitute distinct functionalities, owing to the different materials and optical phenomena involved, and should therefore be addressed separately. Both are currently under discussion or development, with digital varnish removal presently considered the more feasible of the two.

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6. Concluding remarks and Next Steps

This deliverable has presented the first analysis of the needs and requirements of conservator-restorers and other stakeholders for the COLOURS digital tools. The evidence comes from the workflows described by the conservator-restorer partners, the Ljubljana workshop and its survey, and two online co-design workshops on internal pilots. The needs identified for Scenarios 2, 3 and 4 have been translated into functional requirements for each tool (Section 4). Their feasibility will be assessed on the internal pilots in a joint activity of WP2 and WP10, involving the working groups of each scenario and the developers of each tool, and the resulting prioritisation will be reported in D10.2 (Section 5).

The next steps are:

- the feasibility of each requirement will be assessed on the pilots, using the data available for each case study, in a joint activity between WP2 and WP10;
- the final prioritisation will be reported in D10.2 (M24);
- the requirements will be incorporated in the revised specification of the tools in WP3 and in the second iteration of D3.2;
- they will serve as the reference for the validation framework (D12.1) and for the internal validation of the tools (D12.2).

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8. Annexes

Annex 1 – COLOURS Survey questionnaire "Feedback on the COLOURS digital tools demonstrated during the workshop"

Public Link to the survey: Feedback on the COLOURS digital tools

The questionnaire was administered online (Google Forms) to the participants of the Ljubljana workshop on 12 May 2026. Questions marked with an asterisk were mandatory.

1. Current professional role.* (open answer)
2. Main area of work. (single choice: easel paintings; wall paintings; polychrome statues or objects; paper; textiles; archaeological materials; other)
3. How relevant do you think the demonstrated tools are to conservation practice?* (scale 1–5, from "not relevant" to "highly relevant")
4. Which of the demonstrated tools appeared to be the most useful, and you would consider integrating in your workflow?* (multiple choice: Light Damage Estimator (LDE); digital varnish removal; MuLaX; ATON; StyleShade3D; doLCE 2.0; Colour Knowledge Repository (CKR))
5. Regarding the tool (or tools) you found most useful, what made it (or them) relevant? What potential value does it have for your work?* (open answer)
6. How easy was it to understand the output produced by the tools?* (scale 1–5, from "difficult" to "very clear")
7. Which aspect of the tool output could be improved for the tool to be more relevant and fulfil gaps and needs in your workflow?* (open answer)
8. What additional functionalities would you suggest in order to make the tool more relevant to your needs?* (open answer)
9. How clear was the input data that the tool required in order to operate?* (scale 1–5, from "not clear" to "very clear")

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10. How demanding did you find the data required to operate the tool?* (scale 1–5, from "not demanding" to "too demanding for routine practice")
11. In which situations would you consider using such a tool?* (multiple choice: treatment proposal; documentation and reporting; risk assessment and conservation-restoration method selection; testing and validation of methods and protocols; collaboration with scientists, curators, engineers and stakeholders; monitoring and preventive conservation planning; exhibition mounting; material analysis; other)
12. What would prevent you from adopting this type of tool in practice?* (multiple choice: training required; time required; complexity of data required as input; lack of coherence of the tool output with current digital needs; other)
13. What is the most important improvement that would make the tool more useful to you?* (open answer)
14. What level of training would you expect before using this tool independently?* (single choice: none; short online introduction; full-day practical training; other)
15. Would you be interested in future testing or feedback sessions?* (yes; no; maybe)
16. Would you be happy for us to contact you to follow up on your responses to this questionnaire? (yes; no)
17. Contact e-mail. (open answer; not reported, personal data)
18. Please share any additional comments, priorities, or suggestions. (open answer)

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Annex 2 – Workshop and focus group outcomes

a. Feedback on the COLOURS digital tools from the community of conservators-restorers

Ljubljana Workshop May 2026

Tools included in the group working sessions & demonstrations

i. ***Light Damage Estimator (LDE) -*** Ioanna Stefanopoulou (FORTH)
Estimate, predict, and simulate changes in the colours of a painting due to light exposure.

ii. **Digital varnish removal (VarnishLab) -** Giorgio Trumpy (NTNU)
Preliminary approach for the algorithmic removal of aged varnish from paintings.

iii. ***MuLaX -*** Bruno Fanini (CNR ISPC)
Access, discover and examine diagnostic processes on 2D and 3D multi-layered collections.

iv. ***ATON framework -*** Bruno Fanini (CNR ISPC) & Daniele Ferdani (CNR ISPC)
Open-source framework to create Web3D/WebXR apps interacting with cultural heritage objects and 3D scenes on the Web.

v. ***StyleShade 3D -*** Saptarshi Neil Sinha (FhG)
Enhance and stylize 3D models using deep learning techniques, high-quality mesh and material generation.

vi. ***Colour Knowledge Repository (CKR) -*** Sophia Sotiropoulou (FORTH)
An open data management system designed to collect, structure, and openly share colour-related resources in cultural heritage artworks

All six tools were demonstrated at the workshop. Structured feedback from the group working sessions was recorded for the LDE, VarnishLab and MuLaX with the ATON framework, which are reported in detail below. No session-specific feedback was recorded for StyleShade3D and the CKR. For these two tools, participants indicated the following areas of integration: conservation-restoration method selection, collaboration with scientists, curators and other stakeholders, and monitoring and preventive conservation planning (StyleShade3D); documentation and reporting, risk assessment and method selection, and collaboration (CKR). Both tools featured prominently in the online co-design workshops, where the CKR was used for evidence, provenance and comparable documentation and StyleShade3D for appearance simulations and alternative outcomes (Annex 2b). Survey results for all tools are reported under General Feedback.

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Details on users' analysis / requirements emerged during the workshop:

- Light Damage Estimator (LDE)

i. **Tool's relevance to the community of conservators-restorers**

Relevance highly depends on the field of expertise. The majority of participants reported that it could be a useful tool for museums, when handling loans and planning exhibitions of specific artworks. In general, the tool was considered to have medium to high relevance to conservation practices, among participants of diverse backgrounds. Around 45% of participants would consider integrating the tool in their workflow.

ii. **Potential value for their work**

Estimation of colourant sensitivity, during exhibition mounting or when planning exhibitions or possibly when selecting materials for retouches. Virtual representations of possible historical/ future states of an object can help plan conservation-restoration works, as well as scientific research, provide new/additional ideas for further research or professionals' possibilities. Risk assessment, monitoring and preventive conservation planning.

iii. **Output comprehensibility**

The output appears to be quite simple to comprehend.

iv. **Aspects of the output that could be improved to increase its relevance and fulfill gaps and needs in current workflows**

Some participants suggested that the visualization of the shift in the CIELab coordinates would be more useful in a 3D sphere (L*a*b space), displaying prior-to and post-exposure. Some participants also highlighted that the tool would be more relevant if it was addressing manuscripts and photosensitive inks. Finally, the layout of the interface would be more practical if it were landscape-oriented, rather than horizontal.

v. **Additional functionalities suggested by the community**

One highly demanded functionality is for the tool to offer the ability to simulate the colored object's original appearance, meaning the color coordinates of the painted areas prior to photochemical degradation and change in color.

vi. **Complexity of required input data**

HSI is rarely acquired. XRF mapping can be performed in some cases upon request but is not normally acquired along a conservation-restoration workflow. Input data required were considered complex.

vii. **Potential Areas for Tool Integration in current workflows**

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Risk assessment and Conservation-Restoration method selection; Treatment proposal; Collaboration with scientists, curators, engineers, and stakeholders; Exhibition mounting; Monitoring and preventive conservation planning.

viii. **Level of training required prior to use**

Most participants responded that a short online introduction would suffice.

Notes: Participants commented on the required input data as a major concern, as well as time requirements and ease of use.

- **Digital Varnish Removal & Revarnishing tool (VarnishLab)**

i. **Tool's relevance to the community of conservators-restorers**

Highly relevant especially to the community of painting conservators-restorers.

ii. **Potential value for their work**

Can support decision-making steps by simulating the appearance of the artwork both after physical removal of discolored varnishes as well as after revarnishing treatments.

Treatment proposal; Risk assessment and Conservation-Restoration method selection; Collaboration with scientists, curators, engineers, and stakeholders; Monitoring and preventive conservation planning

iii. **Output comprehensibility**

The output appears to be quite simple to comprehend. One improvement suggested regarding the output is a slider tool, similar to the one in the LDE tool, that provides an immediate comparison before/after the virtual intervention.

iv. **Aspects of the output that could be improved to increase its relevance and fulfill gaps and needs in current workflows**

The residual differences between cleaned and virtually cleaned versions of the painting can be decreased using spectral measurement before/after cleaning of additional colored areas of the artwork (not only black and white).

The images should be in high resolution and displayed bigger.

v. **Additional functionalities suggested by the community**

Additional knob/slider that allows the user to visualize different degrees of varnish removal. In fact, the varnish doesn't necessarily have to be removed completely.

vi. **Complexity of required input data**

HSI is rarely acquired. Can the tool develop and operate on calibrated RGB images and point spectral measurements?

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vii. **Potential Areas for Tool Integration in current workflows**
In conservation-restoration workflows of painting conservators-restorers, prior to varnish removal treatments as well as prior to application of fresh varnishes, to simulate and estimate the appearance of the object.

viii. **Level of training required prior to use**
Short online introduction

Notes:

a. Different pigment-medium combinations absorb varnish differently, making the wet-look locally variable.
b. Partial removal of varnish is quite common and needs to be taken into account.
c. What is considered a cleaned reference? Can be subjective and dependent on cleaning approaches.

Participants commented on the required input data as a concern, as well as time requirements and ease of use.

- ***MuLaX & ATON framework***

i. **Tool's relevance to the community of conservators-restorers**
Tool was considered highly relevant.

ii. **Potential value for their work**
Linking material analyses results to the conservators-restorers. Visual representation of data. Documentation, presentation, overlapping of results, holistic understanding.
Tool can ease organization of research results or provide information of similar challenges in research or treatments of other professionals etc. Easier planning of interventions, clearer and more understandable conservation documentation.

iii. **Output comprehensibility**
Output appears to be fairly comprehensible.

iv. **Aspects of the output that could be improved to increase its relevance and fulfill gaps and needs in current workflows**
Means for extracting pdf for **Condition report**, Conservation and Restoration report after the working session. More detailed and customizable documentation options, and clearer visualization of analytical data. Easier integration with existing conservation-restoration workflows, more realistic simulations, and simpler user interaction. Simultaneous visual presentation of

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numerous analytical/research/diagnostic results obtained by different analytical techniques/tools. Greater accuracy and more realistic simulations.

v. **Additional functionalities suggested by the community**
Automatic reporting from the included results; Possibility of simultaneously displaying different analytical results for the same selected spot on an object; Possibility of generating a PDF report; Possibility of adding other analytical results (e.g. spectra from spectroscopic techniques).

vi. **Complexity of required input data**

vii. **Potential Areas for Tool Integration in current workflows**
Documentation and reporting; Collaboration with scientists, curators, engineers, and stakeholders; Monitoring and preventive conservation planning; Material Analysis

viii. **Level of training required prior to use**
Main concern is the time required for the preparation of data to be imported in the tool prior to use.

General Feedback

Nine participants completed the survey. Their main areas of work were easel paintings (2), wall paintings (1), polychrome statues or objects (1), buildings (1), material analysis and microbiology (1), and several object types (3).

1. ***Relevance of demonstrated tools to conservation practices***

Average: **4.0/5.0** (1.0: Irrelevant, 5.0: Highly relevant). 44% of the participants rated the tools as highly relevant.

2. ***Tool preferences and potential integration into conservation-restoration practices***

Tool	Mentions	% of Participants
MuLaX	**9**	**100.0%**
Light Damage Estimator (LDE)	4	44.4%
ATON	4	44.4%
VarnishLab	2	22.2%
Colour Knowledge Repository (CKR)	2	22.2%
doLCE 2.0	2	22.2%
StyleShade3D	1	11.1%

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3. ***Perceived relevance of the most useful tool(s) and potential value for professional practice***

Primary interest

MuLaX:

- Integration of multiple analytical datasets
- Visualization of examination results
- Virtual representation of historical states
- Linking scientific data with conservation practices
- Interactive approach to objects

Light Damage Estimator

- Supports preventive conservation
- Risk assessment
- Exhibition planning
- Light exposure management

ATON (grouped frequently with MuLaX)

- Visualization capabilities
- Data integration

Secondary Interest

Digital varnish removal, CKR.

Least mentioned

StyleShade3D.

4. ***Output comprehensibility***

Average: **3.56/5.0** (1.0: Difficult, 5.0: Very clear)

Most users found outputs reasonably understandable.

5. **Main Intended Uses**

- Documentation and reporting
- Collaboration among scientists/curators/stakeholders
- Treatment proposal
- Risk assessment
- Conservation-restoration decision-making
- Material Analysis
- Monitoring & preventive conservation
- Exhibition Mounting

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6. ***Clarity of Required Input***

   Average: **2.89/5.0** (1.0: Not clear, 5.0: Very clear)

   Input requirements can be understandable but are not immediately obvious.

Improving onboarding and input guidance would likely increase adoption.

7. ***Barriers to adoption***

   i. **Complexity of required input data** (according to 78% of respondents) and misalignment with data that are normally acquired during standard practices.
   ii. Lack of coherence with current digital workflows
   iii. Time required
   iv. Training required
   v. Project-specific applicability

8. ***Recurring Improvements requested***

- More automation.
- Enhancement of the use of AI-driven functionalities. Further integration of advanced AI functionalities would enhance the competitiveness of the developed tools with state-of-the-art commercial solutions currently available on the market, such as those offered by Adobe Photoshop.
- **Automatic condition report generation**.
- Simultaneous visualization of multiple analyses.
- Easier user interfaces.
- Better integration between datasets.

General concerns

- The lack of coherence of current tool outputs to current digital needs.
- The importance of ensuring the availability of appropriate equipment for the proper use of the tools, as well as adequate training, so users are sufficiently skilled to operate them correctly and fully exploit their potential.

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b. Online Consortium Workshops on the Internal Pilots

Expected outputs:

- selection of a maximum of **three priority use cases** for further development;
- definition of the **actors, primary users and institutional goals** associated with each use case;
- a **Design Brief** identifying barriers, motivations, required user capabilities and preferred devices;
- creation of **storyboards** describing realistic end-to-end user experiences;
- identification of suitable **toolchains** and the interactions between COLOURS tools;
- identification of **new or improved functionalities** required by the case studies;
- prioritisation of requirements using a **MUST / SHOULD / COULD / WON'T** approach;
- identification of required **content, datasets and assets**, including gaps in currently available material;
- generation of material that could feed the subsequent development, integration and validation activities of the pilots.

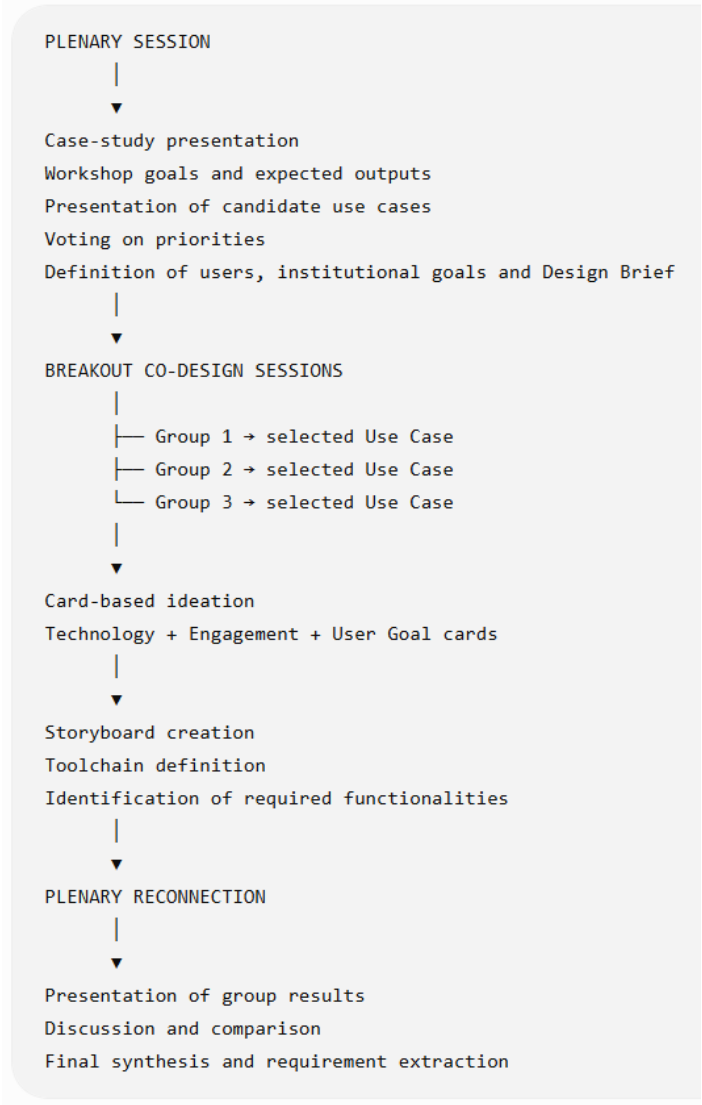
For the two workshops discussed here, the first focused on the **Bratislava polychrome sculptures**, while the second addressed the **Ljubljana Baroque easel painting**. The same methodology was deliberately reused so that outcomes could be compared across different conservation contexts. The structure follows the approach established in the first workshop report.

A. Workshop organisation and process

Both workshops were conducted **fully online**. Participants initially joined a common plenary session and later moved into small breakout groups for the co-design activity. The workshop followed a three-stage structure, represented in the diagram below:

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PLENARY SESSION. The workshops opened with a short introduction explaining the objective of moving from **site-specific experimentation to reusable use cases**. Case-study representatives then presented the conservation context, existing evidence, unresolved research questions and practical constraints. Participants subsequently voted on:

- the most relevant use cases;
- the most important aspects of the case study;
- the main users/audiences;
- institutional goals;
- user goals;
- Design Brief elements: barriers, motivations, capabilities and devices.

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Voting was carried out through online polling.

BREAKOUT. Participants were divided into **three interdisciplinary groups**, generally combining case-study experts, conservators, heritage researchers and tool experts. Each group worked on one selected use case using a common online board and an adapted version of the PERCEIVE **CoDesign Tool (https://zenodo.org/records/15173219)**. The board included: *scenario description; Technology cards; Engagement cards; User/Audience Goal cards; ideation space; storyboard templates.* Participants collaboratively created alternative storyboards showing how users could move through a realistic conservation or interpretation workflow. The activity encouraged participants to combine tools rather than considering them independently, and to identify missing functionality whenever the proposed experience could not be supported by the current toolset.

B. Results

The workshops produced results at three complementary levels: **use-case definition, tool integration, and requirements identification**.

B.1 Pilot 2a,b: J. A. Eglauer wooden polychrome sculptures

The Bratislava workshop focused on the polychrome sculptures and explored scenarios including: reconstruction of original appearance and comparison of alternative presentations; predictive restoration planning; public engagement with restoration processes. The workshop generated multiple storyboards around A/B/C hypotheses, comparison of diagnostic evidence, reconstruction of lost colours, collaborative expert review and visitor-facing interpretation. The merged **recurring workflow** has been:

CKR → MuLAX / ATON → Variant management / StyleShade3D → Collaborative Simulation Environment → Caring Prototype

The strongest **requirements** included:

- ***evidence-to-region linking;***

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- ***layered VIS/UV/IR visualisation;***
- ***comparison of alternative hypotheses;***
- ***version management;***
- ***confidence and uncertainty representation;***
- ***collaborative decision logging;***
- ***exportable comparison packages;***
- ***contextual or AR visualisation;***
- ***visitor-facing explanations of uncertainty /"sense of care"***.

The workshop also identified opportunities to extend tools such as the **Light Damage Estimator** and **StyleShade3D** beyond their initial use cases.

B.2 Pilot 1a: Adoration of the Holy Cross

The Ljubljana workshop applied the same methodology to a very different conservation problem: a **Baroque easel painting with complex historical modifications, overpainting, varnish layers and altered dimensions**. Three principal use cases were developed:

Group 1 — Cleaning hypotheses: separating original and non-original layers and comparing alternative varnish/overpaint cleaning scenarios before irreversible treatment.
Group 2 — Format reconstruction: evaluating current, likely original and interpretive format scenarios, including the identification of added canvas sections and possible reconstruction of original dimensions.
Group 3 — Hybrid remote expert commission: supporting distributed conservation experts in collaboratively evaluating cleaning, overpaint and format interventions through a shared digital twin, diagnostic evidence and predictive simulations.

Across the three groups, the common professional workflow has been:

Evidence retrieval → diagnostic mapping → scenario creation → simulation → collaborative review → decision capture → optional public communication

The most recurrent tools included in the stories were:

- **Colour Knowledge Repository (CKR)** for evidence, provenance and comparable documentation;
- **MuLAX** for layered visualisation and diagnostic inspection;

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- **ATON** for web-based and XR access;
- **StyleShade3D** for appearance simulations and alternative outcomes;
- **Collaborative Simulation Environment (CSE)** for expert review, roles, decision logs and governance;
- **Light Damage Estimator (LDE)** for predictive simulation of light-induced colour change, with cleaning-oriented simulation subsequently addressed by the Varnish Removal/Revarnish Tool (varnishLab)(see Section 4.1.5);
- **Caring Prototype** for translating professional outcomes into public-facing experiences.

The Ljubljana workshop highlighted several particularly important development **requirements**:

- a **painting-oriented cleaning simulation** capable of previewing varnish or overpaint removal;
- **feature-based segmentation** for distinguishing original canvas, additions, seams and altered boundaries;
- structured **A/B/C scenario management**;
- improved **evidence-to-decision traceability**;
- region-based confidence and uncertainty tagging;
- **remote expert invitation, permissions and session management**;
- formal **meeting-output packages**, decision logs and audit trails;
- **reusable online/public communication formats** derived directly from the professional workflow.

The workshops contributed to shift the project perspective from a catalogue of tools toward integrated **toolchains supporting evidence-based conservation decisions**. Overall, 3 recurring functional layers can be identified:

1. **Evidence layer** — retrieve, align, document and contextualise scientific and historical data.
2. **Decision layer** — construct scenarios, compare alternatives, simulate outcomes and support collaborative expert judgement.
3. **Communication layer** — translate selected evidence, decisions and uncertainty into reusable professional documentation and accessible public experiences.

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