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ETHICAL ASPECTS OF 3D TECHNOLOGIES IN SCULPTURE CONSERVATION

MA Thesis

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Abstract

Ethical Aspects of 3D Technologies in Sculpture Conservation

This thesis explores the ethical implications of applying 3D[1] technologies in sculpture conservation. While such tools offer new possibilities for documentation, replication, and interpretive display, they also challenge conventional conservation principles, including authenticity, reversibility, and material compatibility. Through the analysis of theoretical literature, and selected case studies, the research identifies key ethical tensions emerging from the use of 3D technologies. The thesis argues that existing frameworks, though valuable, remain incomplete in addressing the long-term risks and conceptual ambiguities of digital-physical interventions. In response, a set of practical guidelines is proposed to support transparent, sustainable, and ethically responsible applications of 3D tools in conservation. Finally, the thesis highlights the need to expand traditional ethics by integrating care-based approaches that emphasise attentiveness, contextual sensitivity, and shared responsibility in digital heritage practice.

Keywords: 3D technologies, conservation ethics, authenticity, replication, reversibility, digital heritage

[1] Three-dimensional

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Introduction

In recent years, 3D technologies have become increasingly present in the field of heritage conservation. Tools such as photogrammetry, digital modelling, and additive manufacturing (3D printing) now form part of the expanded toolkit available to conservators. These technologies offer new opportunities for documentation, reconstruction, and public engagement. However, their application to physical heritage objects — particularly sculptures — raises a number of ethical questions that remain insufficiently addressed in both theory and practice.

This thesis focuses on the conservation of sculptural works and architectural surfaces, with particular attention to the use of 3D technologies in reconstructive and interpretive interventions. Sculptures present specific challenges due to their three-dimensional form, material heterogeneity, exposure to environmental conditions, and often incomplete or fragmentary state. These challenges intensify when conservators are expected to re-integrate missing parts or make interpretive decisions about their presentation. In such contexts, 3D tools can support traditional methods by offering precise, reversible, and non-invasive options — yet they also carry risks that go beyond the technical.

The central aim of this thesis is to examine how 3D technologies intersect with core conservation ethics. These include authenticity, reversibility, minimal intervention, and transparency. By evaluating current ethical guidelines, international charters, and practical case studies, the thesis assesses whether existing frameworks are sufficient to guide professional decision-making in digital–material interventions. The focus is specifically on the ethical implications of 3D use in sculptural conservation — not on broader museological or educational applications such as virtual exhibitions or tactile replicas for inclusive access. These are acknowledged but remain outside the scope of this study.

The topic reflects the author's continued engagement with the subject since 2022. Previous research includes a bachelor's thesis on the use of 3D printing in plaster conservation, a second master’s project involving material testing of polymer filaments (PLA, PETG, ABS, PMMA), published article on ethical and technical aspects of 3D technologies in conservation field and a forthcoming article on ethical aspects of digital surrogates or another related topic, on questions around repatriation in the form of 3D replicas or digital surrogates. This sustained inquiry informs the critical stance adopted in the present thesis, which does not merely report on available tools, but interrogates their implications for conservation theory and practice.

The structure of the thesis reflects its dual focus on ethics and practice. Chapter 1 - Key Terms defines the key terminology used throughout the thesis. Chapter 2 - Research Questions and Methodology presents the research questions and outlines the methodological framework. Chapter 3 - Ethical Frameworks Relevant to 3D Technologies in Cultural Heritage Conservation critically reviews international ethical charters, policy documents, and institutional codes relevant to 3D technologies in conservation. Chapter 4 - Key Ethical Concepts in Practice: Critical Issues and Case Studies analyses core ethical concepts — including authenticity, reversibility, aura, material compatibility, intellectual property, and sustainability — through both theoretical reflection and case studies. Chapter 5 - Long-term Implications explores long-term implications of digital–material interventions, including material ageing, replication strategies, and monitoring practices. Chapter 6 - Practical Guidelines offers a set of practical guidelines for ethically responsible use of 3D technologies in sculpture conservation. The thesis concludes with a Summary of findings and a Conclusion, which discusses future challenges and responsibilities in the field.

The thesis builds upon a range of literature situated at the intersection of conservation ethics, digital heritage, and material science. Key theoretical foundations are drawn from Cesare Brandi and David Lowenthal, whose writings inform debates on authenticity, aesthetic perception, and the temporal layers of cultural objects. The discussion of digital surrogates and the concept of aura engages with Walter Benjamin, Stuart Jeffrey, and reinterpretations by Pietroni, Zalewski, and Pescarin. Technical and ethical concerns related to 3D-printed materials are addressed through studies by Cieslik, Acke et al., Clarke and Paine, and Flatscher et al., among others. Institutional frameworks are analysed through charters and codes issued by ICOMOS, UNESCO, ICOM, and E.C.C.O.[2] Finally, the author's own prior research — including a bachelor's thesis, a second master's project focused on material testing, and a recently published article on the ethical and technical aspects of 3D printing in conservation — has shaped the critical and practice-oriented stance adopted in this study.

[2] ICOMOS – International Council on Monuments and Sites

UNESCO – United Nations Educational, Scientific and Cultural Organization

ICOM – International Council of Museums

E.C.C.O. – European Confederation of Conservator-Restorers' Organisations

1. Key Terms

For a general introduction to widely used 3D scanning techniques, including photogrammetry, laser scanning, and structured light, and their application across art and design fields, see Bugeja, Bonanno, and Garg (2022). While not specific to conservation ethics, the article provides a useful technological overview that complements more specialised conservation literature. To ensure clarity, only essential definitions of the most widespread terms are included here. For explanation of further terms, see Appendix 1: Extended Glossary.

2D+ Digitisation

An enhanced 2D imaging technique, such as RTI[3], that captures subtle surface variations not visible to the naked eye. Commonly used for inscriptions or fine reliefs (Cieslik 2020).

Data Obsolescence

Data obsolescence refers to the risk that digital formats, software, or hardware become outdated, rendering digital content inaccessible. In cultural heritage preservation, it underscores the need for proactive strategies to ensure long-term accessibility of digital assets. (Amico and Felicetti 2024).

Digital Minimal Intervention

An ethical principle promoting transparency and restraint in digital reconstructions. Additions should be reversible, clearly documented, and distinguishable from original data (Hallermann and Kulik 2019; London Charter 2009).

Digital Surrogate

A digital model created to stand in for an original heritage object. Ethical validity depends on transparency, fidelity, and cultural sensitivity (Hallermann and Kulik 2019; Cieslik 2020).

Digital Transformation

A structural shift in institutional processes and identity brought about by the integration of digital technologies (Liao, Zhao, and Sun 2020).

Epistemic Transparency

The obligation to clearly communicate the methods, assumptions, and uncertainties involved in digital modelling. Supports interpretive accountability (Brecko and Mathys 2020).

[3] Reflectance Transformation Imaging

Interpretive Layering

The practice of visually or structurally separating different levels of certainty or historical phases in digital heritage models. This includes the use of colour-coding, transparency, annotations, or overlays to signal hypothetical versus evidence-based elements (Cardozo and Papadopoulos 2021; Pietroni and Ferdani 2021).

Virtual Reconstruction

The digital re-creation of lost or damaged heritage elements, often involving conjecture. Ethical practice requires transparent distinction between documented and hypothetical features (Pietroni and Ferdani 2021).

Provenance Metadata

Provenance metadata refers to structured information detailing the origin, custody, and modifications of digital objects. In the context of cultural heritage, it ensures traceability, authenticity, and contextual integrity of digital assets. (Digital Preservation Coalition 2023)

Virtual Restoration

A non-invasive digital process aiming to visualise lost or damaged elements of cultural artefacts without altering the original material (Stanco, Battiato, and Gallo 2011).

Versioning

Versioning is a systematic approach to tracking and managing successive iterations of digital objects. It is essential for maintaining data integrity, enabling rollback to previous states, and ensuring transparency in the evolution of digital assets. (Digital Preservation Coalition 2023)

2. Research Questions and Methodology

This chapter introduces the main topic and objectives of the thesis, outlines the key research questions addressed, and describes the methodology:

2.1. Scope of the Thesis

The expansion of 3D technologies within cultural heritage practice has been accompanied by growing concern regarding their long-term implications — not only technical, but also ethical and epistemological. The challenges extend far beyond digitisation itself and include issues of archiving, access, and institutional responsibility.[4] These concerns motivate the core questions of this thesis, which seeks to assess the compatibility of 3D methods with established conservation ethics.

- Which ethical frameworks, international guidelines, and institutional strategies currently define the responsible use of 3D technologies in sculpture conservation, and where do they reveal practical or conceptual limitations?
- How can 3D technologies be applied in ways that uphold core conservation principles such as reversibility, minimal intervention, and respect for material authenticity — especially when their use involves additive manufacturing and physical integration?
- What ethical and material risks are associated with the introduction of 3D-printed synthetic materials into fragile or historically layered substrates, and how can these risks be anticipated and ethically managed?
- To what extent do commonly used FDM[5] printing materials — such as PLA, PETG, ABS, and PMMA[6] — demonstrate chemical compatibility and long-term stability when applied to conservation contexts, and what further research is required?

2.2. Research Objectives and Significance

- Objectives: To explore how contemporary ethical frameworks in conservation of cultural heritage respond to the use of 3D technologies and to define principles that uphold authenticity and minimal intervention and reversibility.

[4] As discussed by Ioannides and Quak (2014) in their analysis of technical and institutional barriers to the integration of 3D technologies in heritage practice.

[5] FDM – Fused deposit modelling

[6] PLA – Polylactic Acid
PETG – Polyethylene Terephthalate Glycol-modified
ABS – Acrylonitrile Butadiene Styrene
PMMA – Polymethyl Methacrylate

- Significance: This thesis provides a theoretical foundation for implementing 3D technologies in alignment with ethical guidelines.

2.3. Overview of Methodology

The technological potential of 3D digitisation has been recognised in conservation literature since the early 2000s.[7] An illustrative example of such digitally driven documentation and interpretative potential is (Pietroni and Ferdani 2021, 13) developed a VR-based[8] interface enabling expert audiences to interact with multiple interpretative layers — including mapped preservation states, stratigraphic textures, and embedded metadata. This case exemplifies how early scanning methodologies have evolved into complex tools for collaborative knowledge construction, going beyond geometric precision to include interpretive transparency and interactive exploration.

[7] See Pieraccini, Guidi, and Atzeni (2001), who applied laser triangulation and photogrammetry to Renaissance plaster casts, emphasising precision and non-invasiveness as guiding values.

[8] Virtual reality.

3. Ethical Frameworks Relevant to 3D Technologies in Cultural Heritage Conservation

While the use of 3D technologies in cultural heritage has expanded rapidly, their integration into ethical frameworks remains uneven. International organisations such as ICOMOS, ICOM, UNESCO, and E.C.C.O. have issued a wide range of charters, codes of ethics, and policy statements intended to guide conservation practice. However, many of these documents predate the emergence of additive manufacturing, digital surrogates, and computational reconstructions. As a result, they often provide only partial guidance on how to apply traditional principles — such as authenticity, reversibility, and minimal intervention — in the context of digital tools and hybrid materials.

Building on the methodological orientation introduced in Chapter 2 Research Questions and Methodology, this chapter critically examines how selected international frameworks have been interpreted, adapted, or contested in response to digital innovation. These documents are not treated as fixed or universally applicable, but as evolving instruments whose assumptions and priorities can be challenged by emerging practices.

The analysis is informed by the author's professional experience in sculpture conservation, including recent involvement in projects where digital techniques played a central role. Accordingly, the chapter considers not only the explicit content of these frameworks, but also their practical implications — particularly where institutional policy and ethical reasoning intersect. The focus is on a set of particularly influential documents, including seminal charters and guidance documents issued by ICOMOS, UNESCO, ICOM, and E.C.C.O., as well as complementary initiatives by ICCROM,[9] the European Commission and the Getty Conservation Institute.

Through this review, the chapter highlights convergences, contradictions, and omissions across these frameworks, particularly in light of material-digital hybrid practices.

The structure of the chapter follows a taxonomy by institutional authorship. For each document, this chapter will present:

- its full official title and issuing body,
- the historical and professional context of its creation,
- the key ethical principles articulated therein,

[9] International Centre for the Study of the Preservation and Restoration of Cultural Property

- its specific relevance to 3D scanning, visualisation, printing, and digital documentation,
- and a critical assessment of its strengths, shortcomings, and practical implications.

3.1. ICOMOS Doctrinal Texts

3.1.1. The Venice Charter (1964)

The *International Charter for the Conservation and Restoration of Monuments and Sites*, commonly known as the *Venice Charter*, remains a foundational document in heritage conservation ethics.[10] Some articles of the Charter remain applicable to digital interventions.[11] However, the Charter's utility is limited when addressing digital heritage. Its materialist ontology, rooted in the conservation of tangible heritage, leaves it silent on topics such as digital surrogacy, interpretative modelling, or paradata standards. This limitation has led scholars to critique its inadequacy in contexts where the boundaries between original and reproduction are ontologically ambiguous. As Jeffrey (2015) argues, the immateriality and infinite reproducibility of digital heritage objects challenge traditional notions of authenticity. He contends that the Charter's emphasis on physical fabric and patina renders it conceptually insufficient for guiding ethical decisions about digital replicas, surrogates, or virtual reconstructions.

In this light, the Venice Charter remains an important symbolic and ethical touchstone, but its applicability to 3D technologies is indirect and interpretive. While it continues to inspire ethical restraint and respect for the integrity of cultural objects, it must be supplemented by more recent charters and frameworks that explicitly engage with digital mediation and immaterial forms of cultural heritage.

3.1.2. The Nara Document on Authenticity (1994)

The *Nara Document on Authenticity*, jointly issued by UNESCO and ICOMOS in 1994, represents a paradigmatic shift in conservation philosophy by explicitly challenging the previously dominant Eurocentric and materialist understanding of authenticity. Building upon the materially grounded ethics of the Venice Charter, the Nara Document represents a conceptual departure that embraces cultural relativism and contextual authenticity.[12] It advocates for the consideration of context, function, spirit, and cultural continuity alongside

[10] The charter was drafted in 1964 and adopted by ICOMOS in 1965. It defines key principles such as minimal intervention, authenticity, and distinguishability of new work.

[11] For instance, Article 9 affirms that restoration must reveal value without relying on conjecture and that new additions should be distinguishable, a view reinterpreted for 3D-printed prosthetics (Díaz-Guardamino et al. 2019).

[12] It was developed at a UNESCO–ICOMOS conference in Nara, Japan (1994), and reflects a multicultural dialogue challenging Eurocentric notions of authenticity.

material integrity, thereby decentralising the authority of Western conservation principles (NARA Document 1994).

From the standpoint of 3D technologies, this broadened notion of authenticity is essential. Digital interventions — such as 3D reconstructions, visualisations, and prints — frequently operate within realms of immateriality and representation. By extending the concept of authenticity beyond material criteria, the Nara Document lays a philosophical foundation for evaluating the ethical legitimacy digital surrogates, particularly when they are employed in the aftermath of destruction, displacement, or loss. For example, virtual reconstructions of war-damaged or demolished heritage structures may be considered authentic if they embody the cultural memory and interpretative narratives of the affected communities (DeSilvey and Harrison 2020).

However, while the Nara Document represents a significant advancement in ethical thinking, its operational applicability remains limited. Luxen (2019), a key participant in the original drafting process, reflects on the ambiguities that emerged during its implementation. He cautions against the misuse of cultural relativism to legitimise speculative reconstructions or to justify heritage commodification. In politically charged contexts, the invocation of authenticity as defined in Nara can be instrumentalised to support contentious heritage claims. Luxen's critique calls for renewed ethical clarity, especially when the stakes involve global symbolic value or contested narratives.

Furthermore, the Document lacks methodological guidance on how to negotiate uncertainty in digital reconstructions or how to integrate community-defined values into formal documentation protocols. These deficiencies have been addressed more explicitly in later documents such as the London Charter and the Seville Principles, which provide concrete procedural frameworks for ensuring transparency and validation in digital heritage work (Denard 2009; López-Menchero and Grande 2011).

Despite its generality, the Nara Document remains a philosophical cornerstone in the ethical evaluation of digital heritage practices. It opens up the conceptual space necessary to move beyond material fidelity, making room for digitally mediated expressions of heritage that are grounded in cultural meaning and continuity. For conservators, it encourages a reflective stance: one that accounts not only for the physical condition of an object but for its intangible significance, community resonance, and historical trajectory.

In conclusion, the Nara Document's value lies in its ethical repositioning of authenticity as a multifaceted and culturally situated concept. This repositioning is crucial for the responsible integration of 3D technologies into conservation, as it legitimises non-material practices and pluralistic heritage narratives. Yet, its strength is also its weakness: without operational specificity, it risks being too open to interpretation. The challenge for contemporary practitioners is to translate Nara's philosophical insights into rigorous, transparent, and inclusive methodologies that can guide ethical decision-making in the digital age.

This conceptual broadening prepares the ground for more operational frameworks, such as the London Charter, which attempt to translate these ethical principles into concrete guidelines for digital heritage practice.



Fig. 1: Representatives at the Nara Conference on Authenticity (1994), where the Nara Document on Authenticity was adopted. From left: Herb Stovel, Jean-Louis Luxen, Christina Cameron. Image: Jean-Louis Luxen. The meeting brought together experts from diverse cultural and disciplinary backgrounds to expand the understanding of authenticity in heritage conservation.

3.1.3. The Ename Charter (2008)

The ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites, also known as *The Ename Charter,* (ICOMOS 2008) explicitly addresses the responsibilities involved in communicating heritage significance. Initially drafted in 1996 as part of a collaborative initiative in Ename, Belgium, the Charter was officially ratified by ICOMOS at its 16th General Assembly in Québec in 2008. It advocates for inclusive narratives, intellectual honesty, and transparency in interpretative methods. These principles align closely with the

ethical demands of 3D technologies, particularly in virtual reconstructions or augmented reality experiences.

Importantly, the Charter insists that all interpretative interventions be clearly distinguished from original fabric and that uncertainty be acknowledged. In the context of 3D modelling, this supports the provision of paradata — documentation of sources, assumptions, and modelling decisions. It also strengthens the argument for accessible digital replicas as tools for education and engagement, especially when physical access is limited. The Charter also calls for community engagement and participatory interpretation, reinforcing the legitimacy of co-created digital outputs. This principle aligns with the concept of paradata as defined in the London Charter (Beacham, Denard, and Niccolucci 2006).

Beacham explicitly states that *"The Draft adopts the format and style of the ICOMOS ENAME Charter to provide a ready-to-hand language, but also to facilitate ease of recognition within cultural heritage contexts"* (Beacham, Denard, and Niccolucci 2006). This alignment underscores the intentional effort to ground emerging digital guidelines in established heritage interpretation frameworks, ensuring both conceptual continuity and institutional credibility.

Moreover, the Ename Charter explicitly encourages the involvement of associated communities and stakeholders in the development of interpretative programmes (ICOMOS 2008, Principle 6), aligning with contemporary digital heritage practices that promote the co-production of knowledge.

For conservators working with 3D technologies, the Ename Charter provides both a philosophical and procedural framework. It affirms the value of digital visualisation as a means of enhancing public understanding, while cautioning against uncritical or aestheticised representations that might obscure historical complexity.

3.1.4. Sofia Principles (1996)

The ICOMOS Principles for the Recording of Monuments, Groups of Buildings and Sites (1996), commonly known as the *Sofia Principles*, were ratified at the 11th ICOMOS General Assembly in Sofia. Despite their pre-digital origin, they remain a cornerstone in the ethics of documentation and recording in heritage conservation. These principles offer rigorous standards for the comprehensive, transparent, and ethically grounded recording of cultural heritage — standards that remain relevant in contemporary digital workflows, including photogrammetry, 3D scanning, and virtual reconstruction.

This emphasis on rigorous documentation echoes Article 16 of the Venice Charter (1964), which first mandated that all conservation interventions be recorded and archived for future reference. The Sofia Principles build upon this foundation, extending the conceptual depth of documentation and broadening its application beyond interventions to include all aspects of recording, representing, and safeguarding heritage values.

Core principles established in early documents such as the Venice Charter (1964), the ICOMOS Principles for the Preservation of Historic Timber Structures (1999), and the Charter on the Interpretation and Presentation of Cultural Heritage Sites (2008) continue to inform heritage discourse today. These documents underscore the values of reversibility, minimal intervention, and authenticity — principles that, while originally material in focus, can be extended to digital contexts. In particular, the shift towards values-based conservation emphasises that authenticity encompasses not only physical fabric but also historical meaning, cultural memory, and symbolic significance.

This philosophical alignment becomes especially pertinent when considering 3D reconstructions, additive manufacturing in sculptural restoration, or digital surrogates created for documentation purposes. For example, a digitally reconstructed fragment of a plaster relief, produced to substitute a lost component, must be assessed not solely for its material compatibility, but for its capacity to embody and communicate the cultural and aesthetic intentions of the original. In this context, the Sofia Principles' insistence on accuracy, contextual documentation, and long-term archiving directly supports the integration of 3D technologies, provided these tools are used in accordance with ethical documentation standards and contribute to knowledge production rather than aesthetic substitution.

However, the integration of ICOMOS principles into digital workflows introduces several epistemic and technical challenges. The principle of reversibility — long a cornerstone of conservation ethics — requires critical reinterpretation when applied to 3D-printed interventions. In physical conservation, reversibility implies that added materials can be removed without harm to the original. But what does reversibility mean in digital contexts? Is a 3D model „reversible“ if its provenance and metadata are well-documented? Or does reversibility refer to the capacity to update, delete, or challenge interpretations embedded in a visualisation?

Similarly, the concept of minimal intervention must be reconsidered. While a digital scan may appear non-invasive, its creation and dissemination can introduce new layers of interpretation,

exposure, and cultural politics. As such, the impact of digital tools must be assessed not merely in technical terms, but in terms of their interpretative influence and institutional consequences. These unresolved tensions are further explored in the ICOMOS Policy Guidance on Heritage and the Sustainable Development Goals (2021). This recent document integrates heritage conservation with the United Nations' 2030 Agenda, calling for inclusive, rights-based, and environmentally responsible practices. It highlights the transformative potential of digital tools, particularly 3D technologies, to improve access, enhance disaster preparedness, and build institutional capacity across global contexts.

For practitioners, the SDG Policy Guidance offers an ethical rationale for using 3D technologies as part of a socially engaged and future-oriented heritage strategy. Its emphasis on equity and participation resonates with current efforts to democratise heritage knowledge and make digital outputs more accessible. However, the document stops short of offering operational protocols or technical standards. It provides a strategic vision, not a procedural roadmap — thereby necessitating the complementary use of documents such as the London Charter, the Seville Principles, or CEN/TC 346 standards.[13]

From a professional perspective, ICOMOS principles must be treated not as static prescriptions, but as evolving frameworks that adapt to emerging materialities and technological forms. The dual nature of 3D interventions — as both digital data and physical artefacts — requires new documentation protocols, expanded definitions of intervention, and reflective methodologies.

A case in point is the reversible attachment of 3D-printed fills to original surfaces using non-invasive technologies, such as magnetic joints. These strategies demonstrate how digital methods can be brought into ethical alignment with traditional conservation values, but only if supported by robust documentation, transparency, and professional scrutiny (Vyhnánková 2023). (See Fig. 2)

[13] CEN/TC 346 is the Technical Committee within the European Committee for Standardization responsible for developing standards in the field of cultural heritage conservation. These standards serve as reference guidelines for quality, methodology, and terminology in conservation practice.



Fig. 2: Magnetic joints used to reversibly attach a 3D-printed fill to the original plaster surface.

Theoretical frameworks such as Latour and Lowe's (2011) concept of the „migrating aura" further complicate the binary between original and replica. Their theory posits that digital reproductions may possess their own form of authenticity if they are contextually embedded and ethically framed. This challenges the conservation field to consider how meaning is reconstituted in digital copies, and how such meaning can be stewarded responsibly over time.

Their argument reframes authenticity as a relational and process-based phenomenon rather than a static material condition — a perspective especially valuable when navigating the ethical challenges of digital materiality.

A notable example of responsible digital reconstruction is the re-materialisation of the Sarcophagus of Seti I, as documented by Latour and Lowe (2011). (See Fig. 3). Originally discovered by Belzoni in 1817, the sarcophagus was subsequently fragmented and dispersed across multiple collections, including the Sir John Soane's Museum and the Louvre. Factum Arte undertook a non-invasive recording of each known piece using photogrammetry and surface scanning. Rather than reconstructing the unknown or inventing lost details, they

digitally reunited the fragments to produce a precise facsimile — a complete visual and spatial surrogate of the original artefact. Presented in exhibitions, this “version n+1” allows viewers to experience the form, scale, and symbolic richness of the sarcophagus without compromising any of its surviving physical components. In contrast to invasive restorations, this project shows how digital technologies can extend authenticity through reassembly, not replacement, and how aura can migrate when mediated through ethically designed reproductions.



Fig. 3 Digitally re-materialised facsimile of the Sarcophagus of Seti I, created by Factum Arte using high-resolution 3D data from fragments held in different museums. The project reunites the artefact’s form and symbolic coherence without altering or endangering the original material.

In conclusion, ICOMOS principles remain indispensable to the ethical governance of 3D technologies in heritage conservation. However, their application demands critical adaptation, interdisciplinary interpretation, and continued normative development. Rather than resisting the digital turn, ICOMOS must lead its ethical integration — ensuring that traditional values of authenticity, care, and cultural continuity are not lost, but reimagined for a hybrid future.

3.2. UNESCO Instruments

3.2.1. Charter on the Preservation of Digital Heritage (2003)

UNESCO’s Charter on the Preservation of Digital Heritage, adopted at the 32nd General Conference in Paris, is also referred to as the *UNESCO Charter on Digital Heritage (UNESCO*

2003). It was one of the first international instruments to acknowledge digital resources as a legitimate and endangered component of cultural heritage. The Charter defines digital heritage as *"unique resources of human knowledge and expression"* and includes both born-digital materials and digital surrogates. It emphasises long-term accessibility, proper documentation, and institutional responsibility, thereby legitimising digital outputs such as 3D scans or virtual reconstructions as heritage entities in their own right.

While the Charter establishes a strong ethical rationale for preservation, it remains abstract in its operational guidance. It does not distinguish between documentary and interpretative digital surrogates, nor does it address issues such as paradata, transparency of authorship, or collaborative knowledge production. Its conceptual significance, however, has proven foundational. As shown by Comes, Buna, and Badiu (2014), the Charter's values have been concretely implemented in digital preservation projects — such as Virtual Ancient Dacia — which integrate 3D scanning, modelling, and cloud-based access to heritage artefacts.

For 3D technologies, this Charter validates the conservation value of digitally captured objects — such as 3D scans of sculptures or architectural details — and mandates their preservation as part of the heritage corpus. This reinforces the view that digital assets are not merely technical records but constitute an integral part of the cultural record, whose preservation involves the same ethical considerations as those governing physical artefacts. The call for proper documentation, metadata provision, and open standards intersects directly with conservation practices, where digital assets often risk obsolescence or inaccessibility due to proprietary formats or under-resourced repositories.

Unlike the London Charter (2009), which explicitly addresses the distinction between evidence-based and hypothetical content, the UNESCO Charter remains conceptually general and does not engage with paradata or modelling assumptions, nor does it provide ethical guidance on issues of authorship, or stakeholder involvement. Its strength lies in establishing the legitimacy of digital heritage, but it requires supplementation by more practice-oriented frameworks.

Practical implementations of the Charter's principles can be seen in projects such as Virtual Ancient Dacia, which applied 3D scanning, digital sculpting, and cloud-based repositories to preserve and disseminate vulnerable cultural heritage assets (Comes et al. 2014).

3.2.2. Recommendation on the Historic Urban Landscape (2011)

UNESCO's Recommendation on the Historic Urban Landscape (HUL), adopted in 2011, introduces a holistic approach to urban heritage conservation. It emphasizes the integration of

cultural, social, and environmental dimensions of heritage within urban planning and development processes. The Recommendation advocates for multidisciplinary and participatory planning approaches, encouraging the use of digital tools — such as 3D modeling and Geographic Information Systems (GIS) — as integral components of heritage management strategies.

From an ethical standpoint, the HUL Recommendation underscores the importance of non-invasive documentation and predictive modeling tools that respect the complexity and layered nature of urban heritage. It positions 3D technologies not as ends in themselves but as decision-support tools that should be embedded within local contexts and knowledge systems. This approach aligns with the values of transparency and inclusivity, promoting community engagement and the incorporation of diverse perspectives in heritage conservation efforts.

While the Recommendation places less emphasis on individual artifacts or sculptural conservation, its focus on context-aware modeling and public accessibility resonates with the principles discussed in subsequent digital heritage charters. By advocating for the integration of heritage conservation into broader urban development frameworks, the HUL Recommendation provides a foundational perspective for understanding the role of digital technologies in preserving and enhancing historic urban landscapes.

3.2.3. The London Charter (2009)

The London Charter for the Computer-Based Visualisation of Cultural Heritage, formally published in 2009 and initially introduced in 2006 (Beacham, Denard, and Niccolucci 2006), remains one of the most influential ethical frameworks for digital heritage practice. Often referred to simply as the *London Charter*, it provides a methodologically rigorous and intellectually transparent foundation for the use of computer-based visualisation in cultural heritage, including virtual reconstructions, simulations, and interpretative 3D models.

The Charter articulates six core principles: (1) clearly defined objectives and purposes, (2) the use of appropriate documentation and paradata, (3) transparency regarding uncertainty and conjecture, (4) intellectual and methodological rigour, (5) sustainability and long-term preservation, and (6) accessibility for diverse audiences (London Charter 2009). These principles are designed not merely to ensure technical proficiency, but to embed ethical accountability, scholarly traceability, and critical openness into digital workflows.

A key innovation introduced by the Charter is the concept of paradata — defined as the documentation of interpretative decisions, assumptions, and source materials that underpin a

digital model. This concept, now widely adopted, complements metadata by explicitly revealing the rationale behind modelling choices. Paradata allows reconstructions to be critically evaluated and updated over time, fostering transparency and reproducibility (Di Giuseppantonio Di Franco, Galeazzi, and Vassallo 2018).

From a conservation standpoint, this insistence on documentation parallels traditional restoration practices, such as condition reporting and intervention logs. However, many digital heritage projects — particularly outside academic or well-funded contexts — fail to provide sufficient paradata, undermining the integrity and long-term usefulness of the visualisations. This persistent gap between theory and practice has been critically noted in scholarly literature (Jeffrey 2015).

The Charter also addresses the epistemic risks of over-authentication, whereby highly realistic or aesthetically polished digital models may obscure their interpretative and hypothetical character. This concern is particularly salient in reconstructions of damaged or lost heritage, such as in post-disaster scenarios. Without explicit indicators of conjecture, digital representations may be misinterpreted as factual, thereby distorting public understanding and academic discourse (McDonald Institute for Archaeological Research 2018).

While the London Charter has been widely cited and adopted across disciplines — including virtual archaeology, exhibition design, and digital museology — it remains a non-binding framework. Its implementation demands institutional investment in documentation protocols, interdisciplinary collaboration, and sustained digital infrastructure. As a result, adherence varies significantly across projects, with smaller or under-resourced institutions often facing practical barriers to full compliance.

Moreover, critics have noted that although the Charter advances methodological clarity, it leaves unresolved deeper ontological and ethical questions surrounding digital replication. For example, it does not fully address whether digital reconstructions can or should be considered “authentic” in the same way as physical artefacts, nor does it engage with emerging challenges posed by machine learning or AI-driven modelling processes (Di Giuseppantonio Di Franco et al. 2018).

Nevertheless, the London Charter has significantly shaped scholarly and professional expectations in the field. Its strengths lie in its conceptual clarity, adaptability, and alignment with broader values of transparency and accountability in heritage practice. For conservators,

it provides a valuable ethical and procedural framework — particularly in cases where 3D visualisations are used to supplement fragmentary or damaged sculptural heritage.

In conclusion, the London Charter establishes a critical ethical foundation for computer-based visualisation in heritage. While not exhaustive or prescriptive, its emphasis on documentation, transparency, and intellectual rigour continues to inform best practices in digital conservation and interpretation.

As further clarified by Niccolucci et al. (2010), the London Charter's core values must be extended to digital artefacts generated via machine processes. The authors propose three additions — provenance, accuracy, and transformation — aimed at safeguarding intellectual rigour in the face of technological opacity. These reflect growing concern that digital outputs may appear authoritative simply because they are generated by scanners or algorithms, when in fact their reliability hinges on complex and often undocumented variables. For 3D objects to serve as trustworthy surrogates in conservation and scholarship, the conditions of their creation and modification must be recorded and communicated alongside the model itself. This perspective not only reinforces the Charter's commitment to transparency, but also aligns with ethical practices in traditional conservation, such as the documentation of interventions and material provenance.

3.2.4. The Seville Principles (2011)

Formally titled *The Principles of the Seville Charter on Virtual Archaeology*,[14] developed in response to the growing complexity and ambiguity in computer-based heritage visualisation, the Charter extends the foundational values of the London Charter into the specific domain of archaeological heritage. Its primary aim is to establish ethical, methodological, and collaborative standards for the responsible use of 3D technologies in archaeological research and dissemination (López-Menchero and Grande 2011).

At its core, the Seville Charter emphasises scientific transparency, interdisciplinarity, and historical rigour. It introduces a structured typology of digital interventions — such as virtual restorations, reconstructions, and recreations — and mandates the clear labelling of evidentiary status in all visual outputs. This classification system is designed to prevent misrepresentation and epistemic distortion, particularly in public-facing applications.[15]

[14] The Seville Principles were published by the Spanish Society of Virtual Archaeology (SEAV) in 2011 and authored by Víctor Manuel López-Menchero Bendicho and Alfredo Grande.

[15] The Charter distinguishes between various levels of certainty in digital interventions, such as anastylosis, reconstruction, and visual hypothesis.

Crucially, the document insists that virtual archaeology projects prioritise scientific validity over visual appeal. It calls for clearly defined objectives, robust documentation, and rigorous methodological procedures. These expectations align closely with best practices in conservation, where transparency and reproducibility are key markers of ethical intervention. In this regard, the Seville Charter provides a framework that is especially relevant when working with incomplete, damaged, or reconstructed sculptural heritage.

A notable innovation is the Charter's strong emphasis on interdisciplinary collaboration. It argues that meaningful digital heritage work cannot be developed within disciplinary silos, but must involve archaeologists, historians, computer scientists, conservators, and other stakeholders in a continual exchange of knowledge.[16]

From an ethical perspective, the Charter reiterates the importance of paradata — detailed documentation of the modelling process, including assumptions, sources, and levels of conjecture. It frames transparency not as a technical add-on, but as an essential epistemological responsibility.[17]

Although originally conceived within the archaeological domain, the Seville Principles offer meaningful insights for sculptural conservation as well. Their taxonomy of uncertainty, attention to historical stratification, and emphasis on distinguishing digital conjecture from physical fact make them particularly applicable in projects involving the partial reconstruction or reintegration of heritage fragments.[18]

However, the implementation of the Seville Principles remains uneven. Many of the protocols they demand — such as interdisciplinary documentation, user testing, and structured paradata — require levels of institutional support that may not be available in all contexts. Their practical adoption often necessitates selective adaptation and reinterpretation, particularly in conservation disciplines where the primary focus remains on material authenticity.

In conclusion, the Seville Charter represents a significant evolution in the ethical regulation of virtual reconstruction practices. By expanding upon the London Charter's vision and tailoring its principles to archaeological realities, it provides a comprehensive and adaptable framework. When thoughtfully applied, its values of transparency, scientific rigour, and collaborative

[16] The Charter recommends structured postgraduate education and quality assurance procedures in the field of virtual archaeology.

[17] These platforms are envisioned as part of a globally networked infrastructure to ensure transparency, comparability, and long-term access.

[18] For example, in the digital reconstruction of a damaged stucco element, the Seville Principles support the documentation of conjecture levels and modelling assumptions.

practice can meaningfully inform the use of digital tools in the conservation of sculptural and architectural heritage.

3.3. ICOM and E.C.C.O. Codes of Ethics

3.3.1. ICOM Code of Ethics for Museums (2004, rev. 2017)

The ICOM Code of Ethics for Museums, formally adopted in 2004 and revised in 2017, outlines the ethical foundations of museum practice, including principles relevant to the digital age. While the document does not explicitly address 3D technologies, it affirms that all museum activities — including documentation, reproduction, and public communication — must be accountable, transparent, and oriented toward public benefit (ICOM 2017). Key provisions stress the importance of accurate documentation, the clear identification of replicas, and the responsible handling of cultural materials in both physical and digital form.

These provisions become especially salient in the context of 3D printing. Museums increasingly use 3D-printed surrogates for display, education, and accessibility.[19] In practical terms, this means that any digitally fabricated replica should be clearly distinguished from the original object in interpretive materials and catalogue records, in order to avoid confusion or false attribution.

This provision has gained renewed relevance in light of growing debates around the digitisation of colonial collections, Indigenous artefacts, and sacred heritage objects.[20] The creation and circulation of 3D scans raise complex ethical questions concerning ownership, consent, and cultural sovereignty.

These issues have been critically examined by Bell, Christen, and Turin (2013), who argue that digital reproductions are not neutral surrogates, but socially embedded objects that must be understood in relation to the communities from which they derive.[21] Their work emphasises that digital heritage initiatives must be framed within reciprocal, context-sensitive partnerships rather than unilateral digitisation agendas.

[19] ICOM Code, Section 4.10: “All forms of copying and reproduction must be clearly identified and must not be represented as the original object.” See ICOM (2017).

[20] ICOM Code, Section 6.1: “Museums should respect the integrity of the cultures and communities from which collections originate and should promote consultation and collaboration.”

[21] The term “digital repatriation” is increasingly used to describe the return of digitised heritage objects to source communities, often when physical repatriation is not possible or contested. See Bell, Christen, and Turin (2013).

Complementary perspectives have emerged in more recent case studies. For instance, Choates (2020) highlights the need for clear communication strategies when museums deploy 3D technologies in exhibitions, especially in relation to transparency, source disclosure, and audience interpretation. Similarly, Barilotti (2022) examines the legal and ethical ambiguities that arise in digital repatriation negotiations.[22]. In a related vein, Csoba DeHass and Taitt (2018) explore the potential of 3D technologies in collaborative heritage preservation, emphasising co-creation, community agency, and the importance of culturally appropriate access frameworks.

These contributions reinforce the notion that ethical museum practice in the digital domain cannot rely on the ICOM Code alone. While the Code provides a general framework grounded in professional integrity and public accountability, it must be supplemented by more context-specific instruments.[23]

3.3.2. E.C.C.O. Professional Guidelines and Code of Ethics (2003)

The E.C.C.O. Code of Ethics (2003) outlines key responsibilities of conservator-restorers, including professional competence, methodological transparency, reversibility, and thorough documentation of interventions.[24] It defines key ethical principles, including professional competence, methodological transparency, reversibility, and thorough documentation of all interventions (E.C.C.O. 2003).

Although the document predates the mainstream adoption of 3D technologies, its ethical values remain highly applicable to digital conservation interventions. Principles such as the requirement for transparent methodology and full documentation apply equally to digital operations such as 3D scanning, modelling, and additive manufacturing. For instance, any digitally reconstructed addition made during the restoration of an object should be based on verifiable evidence, subject to critical interpretation, and documented in a manner that allows future revision or removal.

The Code also addresses the ownership and management of documentation. It affirms that conservation records are the intellectual property of the conservator-restorer but must nonetheless be retained and accessible for future professional reference. In the context of 3D

[22] See Barilotti (2022) for discussion of how legal frameworks often lag behind technical capabilities in digital heritage reproduction and reuse.

[23] The CARE Principles (Collective Benefit, Authority to Control, Responsibility, Ethics) were developed by the Global Indigenous Data Alliance to guide the ethical management of Indigenous data. See https://www.gida-global.org/care.(Accesed on 23. 02. 2025).

[24] The Code was published as part of E.C.C.O. Professional Guidelines (II), which define the ethical, methodological, and institutional responsibilities of conservator-restorers across Europe.

conservation, this raises relevant questions concerning the long-term stewardship of digital data, particularly in cases where intellectual property claims, software dependency, or institutional policy may restrict public access to digital records.
While the E.C.C.O. Code does not provide technical specifications for digital practices, it offers a strong normative foundation for extending conservation ethics into virtual domains. Its emphasis on transparency, evidence-based decision-making, and public accountability offers valuable guidance for professionals integrating 3D technologies into their practice.

3.4. Emerging Frameworks and European Initiatives

As digital technologies become increasingly integrated into heritage conservation, several pan-European and international initiatives have sought to provide more operational guidance than philosophical charters alone can offer. These emerging frameworks contribute to aligning digital heritage practices with core conservation values, such as accessibility, transparency, and long-term stewardship.

The Europeana Publishing Framework (Europeana 2015) encourages open access to digital cultural heritage and promotes the use of quality standards.[25]

The Salalah Guidelines for the Management of Public Archaeological Sites (ICOMOS 2018) similarly emphasise ethical stewardship, especially in contexts where public access and digital dissemination intersect. Although focused on archaeological parks, the guidelines highlight the importance of non-intrusive technologies, stakeholder engagement, and context-sensitive interpretation. Their recommendations are especially relevant for 3D technologies used to mediate public understanding of sensitive sites or ruins.

The Getty Conservation Institute's digital strategies (Avrami et al. 2019) further support this operational shift by linking imaging technologies with long-term preservation planning. Their initiatives stress the role of 3D and digital documentation in preventive conservation, damage assessment, and monitoring — particularly in fragile or disaster-prone environments.

These frameworks reinforce the call for sustainable, rights-based, and equitable approaches to digital heritage, yet they also reveal tensions between ambition and implementation. Smaller institutions may lack the capacity to meet advanced metadata standards or to establish open

[25] The framework defines different tiers of usability and openness, linking higher-quality metadata and imagery to greater visibility within the Europeana ecosystem. Its slogan „the more you give, the more you get" summarises this reciprocity (Europeana 2015).

access workflows. The European context, however, is progressively working toward interoperability through coordinated data spaces and cross-sectoral policies.[26]

3.5. Synthesis and Critical Reflection

The documents reviewed above collectively articulate a robust, if sometimes fragmented, ethical framework for the use of 3D technologies in heritage conservation. They affirm key principles: transparency, fidelity, documentation, reversibility, and the need to contextualise technological interventions within broader cultural values.

While ICOMOS and UNESCO documents provide philosophical and policy-oriented foundations, the London Charter and Seville Principles offer much-needed methodological specificity, while foundational charters, including the Venice Charter and the Nara Document, offer historical depth and conceptual frameworks that continue to inform evolving interpretations of authenticity and significance. Institutional codes, particularly from ICOM and E.C.C.O., translate these ideals into professional obligations. However, gaps remain in enforcement, standardisation, and global equity.[27]

From a conservationist's perspective, these documents collectively affirm the need for transparency, participatory ethics, and long-term thinking. Yet, practical implementation remains uneven. There is a pressing need for:

- expanded digital literacy and critical technological competence among conservation professionals,
- stronger institutional support for paradata and metadata management,
- standardised protocols for labelling uncertainty in reconstructions,
- and a more explicit integration of postcolonial and community-driven approaches.

As a practitioner, I argue for a cautious but proactive engagement with 3D technologies. Digital tools should not be seen as replacements for traditional conservation methods, but as extensions that demand new forms of ethical reflexivity and documentation. In the absence of prescriptive rules, ethical decision-making must remain case-specific, grounded in dialogue, and accountable to both professional standards and public trust.

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[26] The CEN/TC 346 technical committee develops European standards for the conservation of cultural property, including digital documentation practices. However, many of these standards are available only through national standardisation bodies or commercial platforms, limiting their accessibility to researchers and practitioners outside institutional frameworks.

[27] Notable examples include the Salalah Guidelines (2018), Europeana Publishing Framework (2015), and recent EU cultural data space initiatives launched in 2023–2024.

3.6. Conclusion

Ethical practice in 3D heritage conservation is not simply a matter of compliance; it requires critical engagement, professional judgement, and sustained dialogue across disciplines. The reviewed documents provide essential scaffolding, but the responsibility to interpret, apply, and evolve these principles lies with today's professionals. In navigating the intersection of technology and tradition, our ethical compass must be calibrated not only by codes and charters, but by cultural sensitivity, transparency, and a commitment to the public good.

4. Key Ethical Concepts in Practice: Critical Issues and Case Studies

4.1. Authenticity

Authenticity remains a pivotal, yet deeply contested, concept in conservation ethics. Its meaning has evolved considerably since the 1964 Venice Charter, which linked authenticity primarily to material integrity and historical continuity. The 1994 Nara Document, in contrast, recognised the cultural relativity of authenticity, arguing that credible assessment must consider the diversity of values, knowledge systems, and sources of information relevant to a given heritage context.[28]

This relational view of authenticity, grounded in both tangible and intangible attributes, has proven particularly influential in discussions of digital heritage. As museums increasingly embrace hybrid forms of display, from digital replicas to immersive storytelling, the question of what constitutes an "authentic experience" has gained urgency (Pescarin, Città, and Spotti 2024, 6214–15; Pietroni 2025, 2–4). Digital interventions, though materially distinct from the original artefacts, may still foster credible connections to the past — provided they are guided by transparent methods, critical interpretation, and meaningful contextualisation.

Indeed, a growing body of research emphasises experiential authenticity as a valid complement to material authenticity. In interactive environments, authenticity is less about the physical trace and more about emotional engagement, cognitive resonance, and the sense of embodied presence (Pescarin, Città, and Spotti 2024, 6215–16). Pietroni (2025, 5) emphasises the need for critical coherence[29] — not merely realism — to s the epistemological integrity of cultural heritage. Such standards include clear communication of what is reconstructed, speculative, or interpretive (Pietroni and Ferdani 2021, 2–3).

Moreover, the authenticity of replicas — whether physical or virtual — has been reframed through concepts such as "aura migration" (Baracchini 2023) and "curated authenticity" (Garland Thomson 2008). These approaches acknowledge that symbolic value may transfer from original to copy through processes of ritualisation, community acceptance, or deliberate museological framing. A facsimile, such as that of Tutankhamun's tomb, may serve preservation and engagement goals if transparently framed (Zalewski 2016).[30]

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[28] Nara Document (1994) broadened the concept of authenticity beyond material integrity, acknowledging form, design, traditions, techniques, and the spirit of place (Sections 7–10).

[29] Specifically: credibility, narrative coherence, and intelligibility, as necessary conditions for meaningful engagement with digital heritage.

[30] The replica near the Valley of the Kings was designed to divert traffic from the original site and included didactic materials to clarify its status (Zalewski 2016).

At the same time, digital heritage raises concerns regarding simulacra, experiential superficiality, and technological seduction. Critics warn against uncritical reliance on realism, novelty, or "wow-effects", which may obscure interpretive nuance and undermine trust (Pescarin, Città, and Spotti 2024, 6217; Pietroni et al. 2019). Authenticity must therefore be earned through critical transparency, not presumed through appearance.

Finally, the shift from object-centred to audience-centred authenticity introduces new ethical demands. As Pietroni (2025, 6) argues, authenticity in digital environments must be understood as a co-constructed experience — shaped not only by curators and technologists, but also by users' perceptual, cognitive, and cultural frameworks. This evolution challenges conservationists to balance respect for original materialities with responsiveness to contemporary modes of engagement. In this context, authenticity becomes not a fixed attribute, but a dynamic, dialogic process.

Case Study – Virtual Reconstruction

A telling example is the virtual reconstruction of polychromy on classical sculptures. Many ancient marble statues were originally painted, but today their pigments are largely lost, giving a misleading impression of pristine white surfaces. Using 3D scanning and digital rendering, researchers have created vivid reconstructions of sculptures such as Greek korai or Roman imperial busts. In the Bayerische Staatsmuseum, for instance, digital projection overlays reconstructed colours onto a classical statue, allowing toggling between states.[31] Ethically, the project followed the London Charter guidelines: added colours were based on scientific pigment analysis, and interpretive choices were clearly documented. The result is an enriched understanding of the statue — an authentic educational experience that leaves the physical artefact untouched. The distinction between original and speculative is carefully maintained, demonstrating how digital reconstruction can deepen engagement while safeguarding the truthfulness of the object's current state (Pietroni and Ferdani 2021; Pescarin, Città, and Spotti 2024).

Case Study – Tactile Replicas for Blind Audiences

Another scenario highlighting the evolving nature of authenticity is the production of photogrammetric replicas for blind and visually impaired visitors. A notable example is the touchable reproduction of the 18th-century bust Cristo de la Sangre in Murcia, Spain. (See Fig. 4). Conservators digitally scanned the Baroque sculpture and produced a detailed 3D-printed replica, allowing blind visitors to explore the form through touch — an experience the fragile

[31] The display uses digital projection based on pigment analysis, enabling interactive comparison between hypothesised colours and current surface state.

original, kept behind glass, could not provide. While the replica lacks material authenticity, it conveys the artist's formal language and sculptural intent with high precision. In line with the Nara Document's principles, authenticity here lies in the transmission of design, intent, and context rather than materiality. Visitors reported a profound connection with the object, suggesting that sensory and emotional authenticity may be achieved even through surrogates — if transparently declared and purposefully framed (Garland Thomson 2008; Pescarin, Città, and Spotti 2024). This case affirms that accessibility initiatives, when well executed, can ethically expand the definition of authentic engagement.

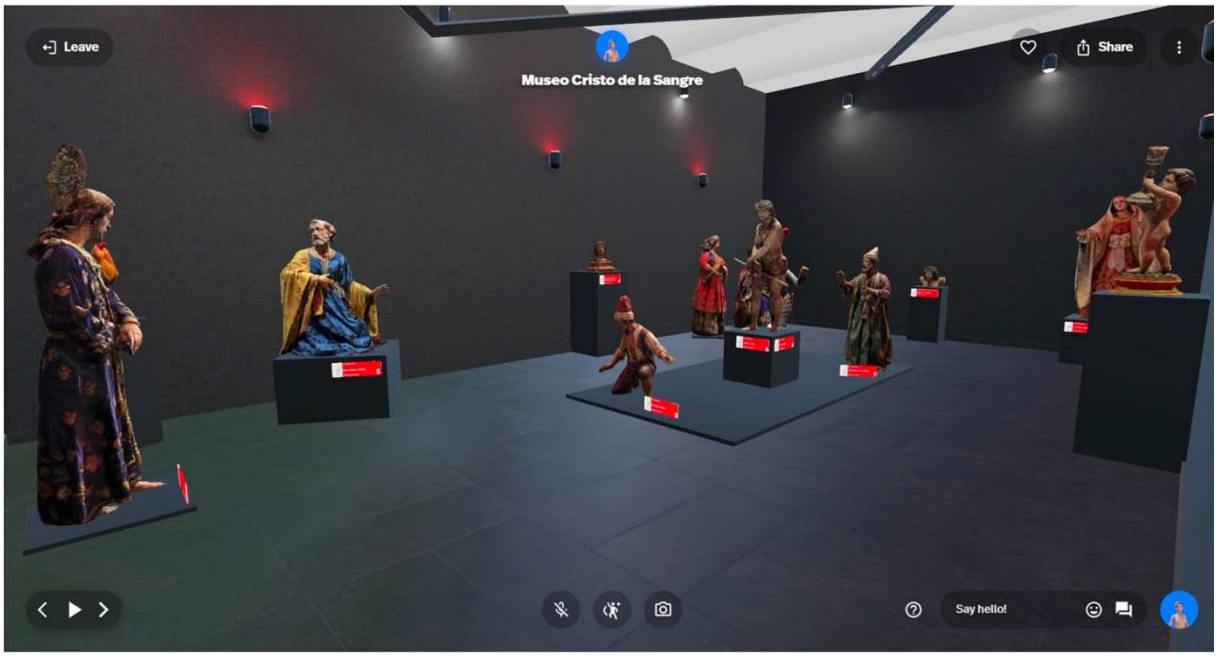


Fig. 4: Exhibition view from *Museo Cristo de la Sangre* in Murcia, Spain, showing a digital installation featuring replicas of 18th-century polychrome sculptures. Among them is a touchable 3D-printed replica of the bust Cristo de la Sangre, designed for blind and visually impaired audiences. While the initiative reflects growing awareness of accessibility in heritage presentation, the visual execution of the replicas — as seen here — raises concerns. The 3D renderings appear plastically oversimplified, with a glossy aesthetic and colour palette that undermine the material authenticity of the original polychrome wood. As discussed in the thesis (Chapter 4.4 Material Compatibility and Long-Term Ethics), the project offers a valuable but imperfect illustration of how well-intentioned digital surrogates can fall short when insufficiently anchored in material realism or nuanced aesthetic translation.

In summary, authenticity remains a cornerstone of conservation ethics, but its meaning has evolved from a strict focus on material originality to a richer, more context-sensitive understanding. As the examined case studies illustrate, authenticity today encompasses the integrity of experience, design, and interpretation — especially when mediated through digital means. Rather than undermining authenticity, 3D and virtual technologies force professionals to define it more precisely and transparently. When guided by ethical frameworks such as the London or Nara Charters, and supported by thorough documentation, digital interventions can deepen engagement without compromising the historical truth of the original. This expanded

understanding of authenticity forms the foundation for assessing another key principle: reversibility.

4.2. Reversibility

Defining Reversibility

Reversibility is a foundational principle in conservation, requiring that any intervention be undoable without harming the original. Rooted in humility and precaution, it acknowledges that all treatments are provisional and that future generations may revisit them with better tools or insights. Classical interpretations define a reversible intervention as one that can be entirely removed, restoring the object to its previous state as articulated, for instance, in the ICOMOS Principles for the Conservation of Wall Paintings.[32] Where full reversibility is unfeasible, interventions should at least not preclude future ones.

In practice, true reversibility is difficult to achieve. Even reversible materials may leave residues, age unpredictably, or subtly alter surface characteristics. For this reason, conservation ethics today favour more flexible standards such as retreatability or minimal intervention. Nevertheless, reversibility remains an essential threshold: if a treatment cannot be undone, it must be demonstrably benign and justified by long-term preservation goals.

Rethinking Reversibility for 3D Technologies

The integration of 3D printing and allied digital techniques demands a reappraisal of reversibility. These technologies offer new opportunities to design additions or augmentations with reversibility in mind — physically, digitally, and conceptually. Three facets can be distinguished:

Physical Reversibility

3D-printed components can be engineered for non-invasive attachment using magnetic joints, pins, or slot-based systems that require no adhesives such as magnetic fixation systems for sculptures[33] and slot-fitted additions for ceramics.[34] While physically removable, such additions must also be chemically inert to prevent staining, corrosion, or degradation over time. In this sense, 3D printing expands the conservator's toolkit: physical reversibility becomes achievable with a precision and non-invasiveness unattainable in traditional techniques.

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[32] The 2003 Principles state: "any measures adopted should be 'reversible' so that they can be removed and replaced with more suitable measures when new knowledge is acquired."

[33] For example, Rodríguez et al. (2018) used magnets to secure fills without adhesives or mechanical intrusion.

[34] Liu et al. (2022) document the use of transparent prosthetic parts that provide support without adhesives.

Digital Reversibility

Virtual interventions — such as 3D scans, AR[35] overlays, or digital reconstructions — introduce a conceptual form of reversibility. Since the original artefact remains untouched, these additions can be "reversed" instantly by disabling the digital layer. Moreover, digital workflows allow changes to be tracked, separated into editable layers, and archived in ways that preserve the original data in line with professional charters recommending interpretive transparency.[36] However, the ease of digital alteration brings ethical risks: widely circulated virtual reconstructions can distort public perception, overshadowing the artefact's actual state. Thus, digital reversibility also demands clarity, labelling, and curatorial responsibility.

Paradata and Documentation

Effective documentation — especially paradata, or the rationale behind interpretative decisions — is essential for meaningful reversibility. It allows others to understand, critique, or revise interventions, even if the additions themselves are not physically reversible. For instance, if reconstructions are based on interpretive models, the rationale must be recorded.[37] This makes the process transparent and retraceable, enabling future modification without starting from scratch. In digital contexts, documentation thus acts as a surrogate for physical reversibility.

Case Examples

Two contrasting examples illustrate the spectrum of reversibility in 3D interventions. In the first, magnetic 3D-printed fills were developed for a damaged plaster sculpture, allowing non-invasive reintegration. The pieces aligned seamlessly with the break edges and could be removed instantly by lifting them from their magnetic seats demonstrating full material and visual reversibility.[38]

In contrast, a conservation project at the Fraunces Tavern Museum in New York used 3D scanning to replicate a missing portion of an 18th-century glass decanter. but the use of permanent adhesives raised ethical concerns.[39] This case underscores a critical ethical tension — technical precision alone does not ensure ethical soundness. The use of permanent

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[35] Augmented Reality (AR) A technology that overlays digital content onto the physical environment in real time, often used in heritage settings to display reconstructions or interpretive layers. AR enables non-invasive, reversible interventions but requires clear labelling to avoid misrepresentation.

[36] Principle 4.6 of the London Charter emphasises the need to document both creative and interpretative choices.

[37] For example, reconstructions based on iconographic analogy should clarify visual sources and levels of certainty

[38] As in a plaster sculpture restoration using magnetically attached 3D-printed fills (Vyhnánková 2023).

[39] At Fraunces Tavern Museum, a resin 3D fill was bonded to a glass decanter with epoxy, limiting retreatability (Barack 2016).

adhesives in 3D-based restorations must be carefully justified, tested for long-term compatibility, and thoroughly documented.

A notable real-world application of reversibility in digital practice is the restoration of the Ain Fouara statue in Sétif, Algeria. Following an act of vandalism in 2017, conservators were able to restore the sculpture's damaged face and chest with high precision thanks to pre-existing terrestrial laser scans. (See Fig. 5 and Fig. 6). As Khodja et al. (2019) document, this point cloud data allowed the team to reconstruct the missing forms without speculative modelling. The intervention was entirely dependent on archived digital records — underscoring that reversibility in digital heritage must also account for the ability to revert to or regenerate original form when loss or destruction occurs. This case not only affirms the technical potential of digitisation, but frames it as a crucial ethical and preventative strategy in the stewardship of vulnerable artefacts.

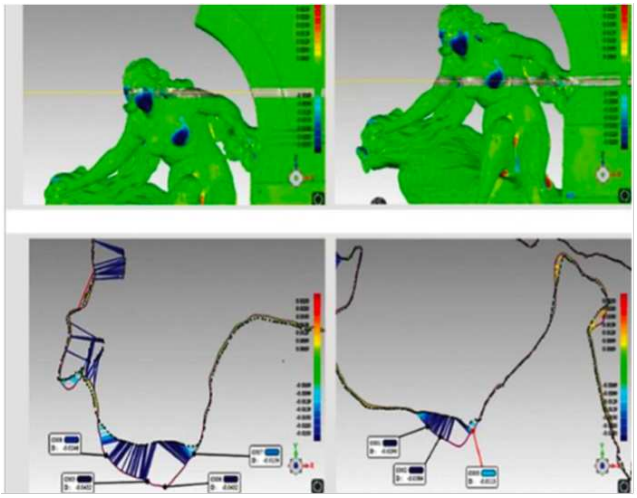


Fig. 5: Digital comparison and deviation analysis of the damaged and undamaged states of the Ain El Fouara statue in Sétif, Algeria. The top images show colour-coded deviation maps of the 3D model, highlighting loss areas (blue) on the statue's face and chest. The bottom graphs depict sectional views and comparative alignment to detect surface discrepancies, aiding the precise restoration process.

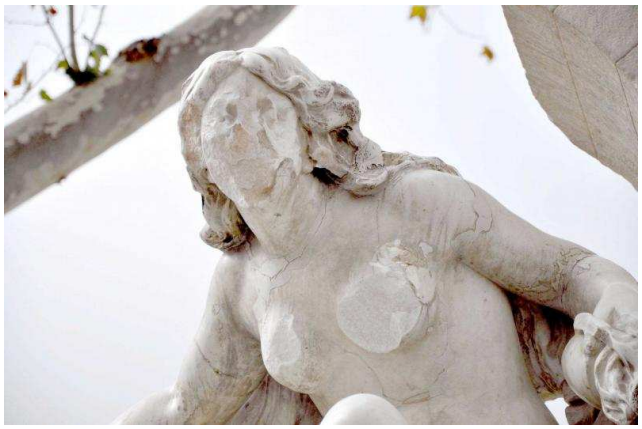


Fig. 6: This iconic statue of a nude woman, sculpted by Francis de Saint-Vidal in 1898, has become a symbol of the city. Over the years, it has been repeatedly vandalised — most notably in 1997 and 2017 — sparking intense public debate about cultural identity, religious values, and the role of heritage in contemporary Algerian society.

Conclusion

Reversibility in the era of 3D technologies is not a binary property but a spectrum encompassing physical, digital, and informational dimensions. While 3D printing introduces tools that facilitate non-invasive, modular, and retreatable interventions, it also raises new obligations regarding documentation, transparency, and restraint. Virtual restoration, if clearly contextualised and recorded, can be reversed without consequence — but poorly framed or unlabelled representations may cause interpretive confusion that is harder to undo. As such, conservators must strive for maximum reversibility — through detachable components, versioned files, or detailed paradata — while accepting that some decisions will always entail trade-offs. This expanded understanding of reversibility reinforces the broader ethical commitment to authenticity, sustainability, and future stewardship.

4.3. Aura and Digital Surrogates

The concept of an artwork's aura has long been central to debates on authenticity. Walter Benjamin's seminal essay The Work of Art in the Age of Mechanical Reproduction (1936) defined aura as the unique presence of an original in time and space — a singular existence imbued with history, tradition, and spiritual value. For Benjamin, aura is inseparable from the object's unbroken material continuity and ritual context, arguing that mechanical reproduction dissolves its connection to origin and context.[40] This notion has shaped conservation ethics, reinforcing the emphasis on original patina, setting, and materiality.

Later thinkers, however, have challenged the view that aura is irreversibly lost through reproduction. Bruno Latour and Adam Lowe (2011) argue that aura is not fixed to the original but may migrate when a high-fidelity facsimile is created and framed with care. Their concept of the "migrating aura" suggests that when a copy restores the experience and significance of the original — through accuracy, context, and emotional resonance — it may elicit a comparable sense of authenticity. A well-known example is Factum Arte's replica of Veronese's The Wedding at Cana, reinstalled in its original Venetian location: according to some viewers reported a stronger connection to the replica due to its reinstated context.[41]

These theories represent two poles: Benjamin's static, intrinsic aura versus Latour and Lowe's dynamic, experiential model. The former underpins the conservation field's commitment to preserving the original fabric, while the latter reflects evolving curatorial practices that prioritise storytelling, access, and emotional engagement. Scholars such as Pescarin (2024) and

[40] Benjamin famously writes that aura "withers" when reproduced, as the original loses its authority tied to presence in time and space (Benjamin 1936, 221).

[41] The Factum Arte replica of Veronese's *The Wedding at Cana*, installed in its original setting in Venice, was described by some as feeling "more original" than the original at the Louvre (Latour and Lowe 2011; Zalewski 2016).

Pietroni et al. (2019) have further argued that authenticity can be co-constructed through interaction — an idea that allows surrogates to become legitimate conveyors of heritage when designed and communicated responsibly.

Experiencing Aura through Digital Technologies

Empirical research supports the idea that digital surrogates can evoke aura under the right conditions. Research shows that replicas can elicit emotional responses when well contextualised.[42] Holtorf (2013) suggests that this very contrast may enhance the aura of the original, as replicas stimulate curiosity and comparison. In short, high-quality copies may not replicate aura fully but can generate a derivative or referential aura that connects the viewer to the original's meaning.

This hypothesis has been empirically tested by Di Giuseppantonio Di Franco et al. (2015), who compared visitor responses to original artefacts and their corresponding 3D-printed replicas. (See

Fig. 7). Their study found that while the digital reproductions retained accurate form, they often lacked the weight, texture, and multisensory impact of the originals — reinforcing the notion that aura is not fully transferable, but may emerge in hybrid, relational ways.



Fig. 7: Comparison of original artefacts (A–D) and their corresponding 3D-printed replicas (E–H) used in the experiment. The items include a Buddhist ritual object from Nepal (A, original "spoon"; E, replica), a grinding stone

[42] Cardozo and Papadopoulos (2021) conducted visitor studies demonstrating that multisensory framing increased affective engagement, though original artefacts retained a stronger aura.

from California (B; F), a ceramic vessel from Ethiopia (C; G), and a projectile point (arrowhead) from California (D; H).

Case Study – Holography and the Mytilene Treasure

A striking example of balancing aura and interpretation is the “Box of Stories” installation at the Byzantine and Christian Museum in Athens. (See Fig. 8). This mixed-reality exhibit presented three original artefacts from the 7th-century Mytilene Treasure — anchored physically within a Pepper’s Ghost holographic display. Around the originals, a dramatised narrative unfolded, re-enacting their domestic use and concealment (Pietroni 2018; Pietroni and Ferdani 2019). Importantly, the real objects remained the visual and symbolic centre. Surveys indicated that the immersive storytelling enhanced, rather than distracted from, visitors’ connection to the originals. This case demonstrates that digital augmentation need not replace aura — it can amplify it, when the original remains visibly and interpretively prioritised.



Fig. 8: Digitally restored and 3D-printed replica of the silver trulla from the Mytilene Treasure, exhibited in a holographic showcase as part of the *CEMEC* project. The object’s historical use was interpreted through animated narration and filmed reenactment.

Case Study – Tutankhamun’s Tomb Facsimile

Factum Arte’s life-sized replica of Tutankhamun’s tomb, installed near the fragile original in Luxor, exemplifies the practical and ethical potential of facsimiles. Constructed with millimetre-precision scans and crafted with exceptional detail — including surface textures, pigment layers, and even “printed dust” — the facsimile was praised for evoking the solemnity and splendour of the real tomb (Zalewski 2016; National Geographic 2014). Though lacking non-visual cues such as smell or temperature, it conveyed a profound sense of place and history. Its open presentation as a replica ensured transparency, while protecting the original from degradation. Latour and Lowe (2011) would interpret this as a successful case of aura migration — a surrogate that extends the life of cultural meaning through ethical reproduction.



Fig. 9: Inside the workshop of Factum Arte in Madrid, where advanced technologies are used to produce high-resolution facsimiles of cultural artefacts from around the world. Visible are reconstructions of a lamassu (Assyrian protective deity), Renaissance paintings, and sculptural fragments, exemplifying the workshop's blend of digital and artisanal techniques. The space itself embodies the tension between preservation, reproduction, and artistic authorship in the digital age.

Ethical Reflections on Surrogates and Sacred Contexts

The use of digital surrogates raises important ethical questions. Can aura be preserved — or even generated — by digital means? And under what conditions might surrogates distort or diminish it? Ethical use hinges on transparency, accuracy, and contextual sensitivity. As Lewis (2020) and the London Charter (2009) emphasise, clearly declaring the nature and purpose of surrogates helps maintain trust and prevent confusion. When surrogates are treated not as replacements but as communicative tools — extensions of the original — they may sustain or even enhance its cultural impact.

Nevertheless, risks remain. Poorly crafted or decontextualised surrogates may trivialise the original or mislead audiences. In sacred or emotionally charged contexts, digital replication may be inappropriate without community consent. Buragohain et al. (2025) note that simulating sacred ambience through VR remains ethically delicate: intangible elements like ritual, acoustics, or communal atmosphere are difficult to recreate. The spiritual significance of aura

may be inseparable from material continuity and authorised ritual presence. At Japan's Kodaiji Temple, for instance, a VR experience was created with input from community representatives.[43]

Conclusion

Aura, once thought to be non-transferable, is now understood in more pluralistic and experiential terms. While Benjamin's notion of uniqueness remains foundational, Latour and Lowe's model — supported by case studies like the Mytilene hologram and the Tutankhamun facsimile — demonstrates that aura can be reactivated through ethical design and contextual richness. Digital surrogates are not magic substitutes, but they can serve as meaningful mediators when used with care. The challenge for conservation is not to replicate aura, but to safeguard and extend its resonance — without deception, distortion, or detachment from the original. When this is done well, digital surrogates can contribute to the continuity of cultural memory, sustaining the aura of heritage through time, space, and technology.

4.4. Material Compatibility and Long-Term Ethics

The integration of 3D printing into conservation practice introduces complex questions about material compatibility, long-term stability, and ethical responsibility. Traditional conservation ethics emphasise material continuity, reversibility, and minimal intervention. However, 3D-printed components — often based on synthetic polymers — present new dilemmas that extend beyond technical performance. This section draws on recent research, including the author's own analytical tests, to examine the ethical implications of these materials.

Defining Compatibility in Conservation Terms

Material compatibility in conservation goes beyond physical adhesion or aesthetic integration; it encompasses chemical stability, inertness, and long-term interaction with historic substrates. Fused Deposition Modelling (FDM), the most widely used 3D printing technique in conservation, typically employs common thermoplastics.[44] While these materials are popular due to accessibility and ease of printing, their long-term effects on porous substrates such as plaster or stone remain insufficiently documented.

[43] At Kodaiji Temple in Kyoto, VR content was developed collaboratively to ensure fidelity to Zen aesthetics and appropriate ritual tone.

[44] These include polylactic acid (PLA), polyethylene terephthalate glycol (PETG) or acrylonitrile butadiene styrene (ABS).

Accelerated ageing tests — including UV[45] exposure, temperature fluctuation, and humidity cycling — have revealed significant degradation in certain filaments.[46] While such studies have focused on the ageing behaviour of the filaments themselves, the author's current research shifts the emphasis to chemical compatibility—specifically, the interaction between selected 3D printing materials and plaster substrates.[47]

Conservation-Safe ≠ Ethically Safe

A recurring theme in both literature and practice is the mismatch between what is technically permissible and what is ethically responsible. A material may pass standard technical tests[48] without necessarily aligning with ethical principles of transparency, reversibility, and accountability. Clarke and Paine (2018) note that even accurate reproductions can undermine the authenticity of an object if their introduction is not adequately documented or justified.

This dilemma was illustrated in the Fraunces Tavern Museum project, where a 3D-printed fill was permanently bonded with epoxy to an 18th-century glass decanter. Although visually successful, the treatment was non-reversible, thereby violating a core conservation ethic (Barack 2016). This underscores a broader point: chemical inertness is necessary, but not sufficient, for ethical acceptability.

Case Study: Vyhnánková (2023)

In a recent case, a damaged plaster model was digitally reconstructed and a missing section replaced with a PETG-printed fill. The printed addition was fixed using magnetic joints, allowing full removability and eliminating the need for adhesives. The design respected both the physical and conceptual integrity of the original: it was distinguishable, removable, and based on scientifically derived documentation.

Nevertheless, the project raised important questions. While the PETG material passed the Oddy test and showed no significant interaction with plaster in sandwich tests, uncertainties remain about its behaviour over decades. As Acke et al. (2021) argue, minor changes in filament composition or post-processing can alter ageing properties. Without conservation-specific standards for polymeric materials, long-term predictions remain speculative.

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[45] UV - ultraviolet

[46] In particular, San Andrés et al. (2023) documented yellowing, surface cracking, and cohesion loss in PLA and ABS after UV ageing.

[47] The tested materials include PETG, PMMA, PLA, and ABS. Ongoing experiments use sandwich-type contact setups and enclosed micro-environments to assess potential effects on plaster. Results will be published by August 2025.

[48] Such as the Oddy test (used for detecting off-gassing) or gas chromatography–mass spectrometry (GC-MS) for identifying volatile emissions.

The case highlights a key insight: ethical conservation with 3D materials must go beyond stability testing. It requires rigorous documentation (including paradata), transparent justification of choices, and an explicit plan for future monitoring or removal. In this light, PETG can be considered an ethically valid choice — provided its use is contextualised within a reversible, well-documented framework.

Towards Ethical Material Standards

To address these challenges, scholars and practitioners are calling for the development of ethical material standards specific to additive manufacturing. Acke et al. (2021) emphasise the need for environmental condition testing, while Khunti (2018) stresses the importance of questioning motivations and potential unintended consequences. Without established norms, the burden lies on individual conservators to make case-by-case decisions — often without sufficient guidance. Proposals for ethical standards include several key measures.[49]

Only by combining empirical testing with ethical foresight can conservators ensure that 3D printing serves cultural heritage without compromising its long-term integrity. As this thesis argues, a filament that is chemically inert but ethically opaque does not meet the demands of responsible conservation. Future practice must integrate ethics at every stage — from material selection to final display.

[49] These include: (1) documentation of digital and physical interventions, (2) standardised labelling of printed components, (3) lifecycle assessment of materials, and (4) institutional review processes for proposed treatments.

4.5. Intellectual property and digital ownership of 3D Cultural Heritage



Fig. 10: A volunteer uses a handheld 3D scanner to capture a digital model of a sculpture (Scan the World initiative). The democratization of 3D scanning raises debates about who owns and controls these digital reproductions.

The digitisation of cultural heritage through 3D scanning has introduced complex legal, ethical, and political questions. While the underlying physical artefacts are often in the public domain, their digital surrogates may fall under new layers of ownership and control, raising concerns over digital colonialism, access, and the appropriate use of cultural data.

Copyright and Digital Reproductions

In many jurisdictions, the act of creating a digital model generates a new intellectual property right. Legal experts broadly agree that new intellectual property rights apply to digital 3D models of public-domain heritage.[50]

This legal stance has generated ethical friction. Critics argue that granting copyright over public-domain cultural artefacts via digital surrogates can reintroduce exclusivity and restrict access. In particular, tensions arise when institutions refuse to share scans or apply restrictive licensing. For instance, the Neues Museum in Berlin initially withheld its high-resolution 3D model of the Bust of Nefertiti, prompting an act of unauthorised digital repatriation.[51] (See Fig. 11.)

[50] See Shein (2019) for commentary by Ping Hu and Elizabeth Thompson on the copyright status of 3D scans derived from non-copyrightable heritage objects.

[51] Artists Nora Al-Badri and Jan Nikolai Nelles covertly scanned the bust of Nefertiti after the Neues Museum declined to release its official model (Garland Thomson 2008; Cuno 2020).



Fig. 11 Visualisation of the digitally reconstructed Bust of Nefertiti, partially rendered as 3D scan data. The high-resolution model was obtained and published without official permission by artist-activist Cosmo Wenman in 2019, challenging the Neues Museum's refusal to release the data. The image became emblematic of the debate over copyright, access, and the ethics of digital cultural heritage — particularly in the context of post-colonial repatriation claims.

Digital Colonialism and Repatriation Claims

Such acts of digital resistance highlight a broader phenomenon often described as digital colonialism. As Di Giuseppantonio Di Franco et al. (2018) argue, control over heritage data — especially when extracted from post-colonial or Indigenous contexts — can replicate colonial patterns of knowledge appropriation. Cultural institutions based in Europe or North America may digitise sacred or symbolic objects from other cultures without consultation or consent, only to assert ownership over the resulting data.

However, models of ethical collaboration are emerging. The Smithsonian Institution, for example, has worked with Tlingit communities in Alaska to digitise ceremonial objects in a way that respects Indigenous protocols and ensures shared ownership of digital files (WIPO 2017). These partnerships promote data sovereignty — the right of communities to govern access to, and use of, digital reproductions of their cultural heritage.

Open Access and Licensing

Museums and research bodies are increasingly facing calls to release 3D models under open licences. Initiatives such as Scan the World promote open licensing practices.[52] Advocates of open access argue that cultural heritage belongs to all humanity and should not be restricted by paywalls or proprietary platforms.

Nevertheless, concerns about commercial misuse persist. Institutions fear that free-access 3D data could be exploited by third parties for profit — for instance, in the form of unauthorised merchandise. Some therefore adopt non-commercial licences (e.g., CC BY-NC-SA), which permit educational use but restrict commercialisation. Yet, as critics like Adam Lowe argue, overly cautious licensing may stifle innovation and public engagement.

Legal vs. Ethical Ownership

The case of the British Museum and the Parthenon Marbles underscores the conflict between legal authority and ethical stewardship. In 2022, the museum denied the Institute for Digital Archaeology permission to scan the marbles, despite no copyright protections applying to the ancient works (The Guardian 2022). The IDA intended to create exact replicas as a gesture of reconciliation and return to Greece as part of a proposed gesture of restitution.[53]

Such cases reflect a growing recognition that legal rights do not always align with ethical responsibilities. As Clarke and Paine (2018) point out, the question is not merely who owns digital data, but how it is framed, contextualised, and shared. Ethical digitisation involves transparency, consultation, and respect for source communities and descendant stakeholders.

Towards a Fairer Digital Heritage Policy

To address these tensions, several recommendations have been proposed:

- Establish clear protocols for community consent in the digitisation of sensitive or sacred heritage.
- Apply open licensing wherever feasible, with exceptions for culturally restricted materials.
- Include paradata — records of interpretative decisions — to ensure accountability and future reusability.
- Recognise the cultural and ethical dimensions of 3D data alongside legal ownership.

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[52] The platform uses Creative Commons licences to distribute thousands of freely accessible 3D models of artworks. See https://www.artec3d.com/cases/scan-the-world. (Accessed on 14. 05. 2025)

[53] The Institute for Digital Archaeology sought to scan the Parthenon Marbles in 2022 and produce replicas for Greece. The British Museum refused the request, citing institutional control (The Guardian 2022).

In sum, intellectual property in the context of 3D heritage is not just a matter of law. It intersects with broader debates on authority, access, and restitution. As cultural heritage enters the digital realm, its governance must reflect not only technical and legal considerations but also the ethical commitments of equity, transparency, and shared stewardship

4.6. Sustainability and Long-Term Storage of 3D Heritage Data

The sustainability of digital assets is now recognised as an essential component of cultural heritage conservation. As 3D technologies become embedded in documentation and restoration workflows, the long-term preservation of related files — scans, models, metadata, and documentation — raises both technical and ethical questions. These concerns extend beyond storage logistics and encompass institutional accountability, epistemic transparency, and equitable access.

Ethical Framing of Digital Preservation

International guidelines such as the UNESCO Charter on the Preservation of Digital Heritage (2003) and the London Charter (2009) underscore the ethical obligation to ensure digital heritage remains accessible, intelligible, and authentic over time. Their provisions stress structured metadata, traceable provenance, and platform-independent storage as conditions for responsible digitisation. The European Commission's recommendations for 3D digitisation similarly emphasise that digitisation must be paired with strategies for long-term access and curation (European Commission 2020).

Risks and Vulnerabilities: Obsolescence, Platform Dependency, Metadata Loss

Among the most pressing threats to digital sustainability are technological obsolescence, dependence on commercial platforms, and metadata degradation. As noted by Amico and Felicetti (2024), digital assets stored in proprietary formats or obsolete media can become unreadable within a decade. Formats such as WRL[54] or outdated project files may require emulation or risky conversion, highlighting the need for opensustainable formats.[55]

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[54] WRL – Virtual Reality Modeling Language (VRML)
File extension: .wrl. WRL files are text-based 3D model files defined in the VRML (Virtual Reality Modeling Language) format, which was popular in the 1990s and early 2000s for representing interactive 3D objects and scenes, especially on the web. These files can describe geometry, appearance, lighting, animations, and user interaction.

[55] Open formats such as OBJ, PLY, and glTF are preferred over legacy or proprietary types like WRL, which may become unreadable without emulation. (OBJ – Wavefront Object Format. File extension: .obj. Often used in cultural heritage for mesh exports from 3D scanning or modelling software. PLY – Polygon File Format. File extension: .ply. Stores 3D data as a list of polygons (typically triangles) and supports colour, transparency, normals, and user-defined attributes. Preferred for scientific and archival-quality scans due to its extensibility and support for per-vertex metadata. glTF – GL Transmission Format. File extension: .gltf or .glb. Developed by the Khronos Group as an efficient, modern, and extensible format for real-time rendering and web applications. Increasingly used in digital heritage dissemination and online exhibitions.

Relying on third-party platforms like Sketchfab for long-term storage is also problematic. These services facilitate public access but lack the archival guarantees of certified repositories. Best practice now involves separating access copies from preservation masters and depositing the latter in secure, standards-compliant digital repositories (e.g., CoreTrustSeal-certified facilities).

Equally vital is the preservation of metadata and paradata. Without contextual information, 3D models lose much of their scholarly and conservation value. Metadata should record who scanned what, when, why, how, and with what tools — while paradata should reflect interpretative choices, reconstructions, or corrections according to established preservation principles.[56]

Institutional Commitment and Capacity Gaps

Despite broad consensus on these principles, their implementation remains inconsistent — particularly among small or under-resourced institutions. Nikolaou (2024) reports a persistent knowledge gap in digital preservation practices, noting that technical expertise is often undervalued or missing altogether. In response, leading institutions have begun investing in digital preservation officers, dedicated storage infrastructure, and staff training.

The EU's 10 basic principles for 3D digitisation call for integrated planning, including data management plans, lifecycle thinking, and investment in technological and curatorial expertise (Europeana 2023). Without these structural supports, digitisation risks producing ephemeral or unusable records.

Practical Strategies for Responsible Preservation

To mitigate the long-term risks associated with digital heritage, practitioners increasingly adopt the following strategies:

- Adoption of open and standardised formats (OBJ, PLY, glTF) for maximum longevity and accessibility.
- Redundant storage strategies, combining institutional archives with public repositories like OpenHeritage3D or CHEI at UC San Diego.[57]

[56] These include the OAIS (Open Archival Information System) reference model, which provides a framework for long-term digital preservation, and the FAIR principles — Findable, Accessible, Interoperable, Reusable — which promote structured, machine-readable, and sustainable data practices. Additionally, the CARE principles — Collective Benefit, Authority to Control, Responsibility, and Ethics — emphasise community agency and ethical governance in managing data, particularly in Indigenous and post-colonial contexts.

[57] Cultural Heritage Engineering Initiative (CHEI) at the University of California San Diego (UCSD).
It is a research initiative focused on the digital documentation, conservation, and engineering analysis of cultural heritage sites and artefacts. CHEI develops advanced tools and workflows for 3D data acquisition, processing, and

- Comprehensive metadata schemes aligned with evolving standards such as CHML or STARC.[58]
- Periodic review and format migration, including checksum verification and software version control.
- Ethical data governance, particularly for heritage of Indigenous or descendant communities, respecting the CARE principles.

These protocols must be integrated from the outset of any digitisation effort — not retrofitted after dissemination. Digital preservation is a process, not a product.

Conclusion: Preservation as Ethical Practice

In the emerging digital conservation paradigm, sustainability is no longer an auxiliary concern — it is a moral imperative. To digitise without planning for longevity is to betray the stewardship role of cultural institutions. Just as physical artefacts require careful environmental controls and periodic assessment, digital surrogates require curation, documentation, and institutional foresight.

The professional standard is evolving: digital collections are not an add-on, but a core responsibility. Responsible preservation demands interdisciplinary collaboration, transparent governance, and sustained investment. Above all, it requires a shift in mindset: every scan, model, or dataset produced today must be intelligible and accessible not only tomorrow, but decades from now. Ethical conservation in the digital age begins with planning for the long term — from creation to curation, from access to archival endurance.

4.7. Overview of Selected Case Studies

The following table summarises selected case studies discussed in the previous subchapters, with emphasis on ethical tensions related to materiality, authenticity, reversibility, and digital

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dissemination — often collaborating with institutions like CyArk and the Library of Congress. https://chei.ucsd.edu (Accessed on 25. 05. 2025)

[58] CHML – Cultural Heritage Markup Language

This refers to a domain-specific markup language, typically based on XML or RDF, designed for describing cultural heritage data. It is used to structure metadata related to artefacts, their provenance, conservation history, and related interpretive layers. While not a universally standardised model like CIDOC CRM, CHML is often used in digital humanities and heritage documentation projects to ensure semantic consistency and interoperability.

STARC – Science and Technology in Archaeology Research Center

STARC is a research centre at The Cyprus Institute, specialising in the application of science and digital technologies in archaeology and heritage conservation. In this context, “STARC standards” likely refer to metadata models, digitisation protocols, or documentation frameworks developed within this institute and aligned with FAIR data principles and international best practices in digital heritage.

transparency. It serves as a synthetic reference for understanding how theoretical principles manifest in conservation practice.

This chapter explores a range of real-world examples that highlight both the potential and the challenges of applying 3D technologies in the conservation of sculptural heritage. Through selected case studies, it examines how specific ethical principles — such as transparency, reversibility, and respect for original context — are negotiated in practice. These cases vary in scale, technique, and institutional context, yet they all reflect broader questions addressed throughout this thesis. An overview of the case studies and their core characteristics is provided in Tab. 1, serving as a reference point for the discussion that follows.

Tab. 1: Selected case studies illustrating the ethical dimensions of 3D technologies in cultural heritage practice. The table summarises examples discussed throughout the thesis, noting the technological methods used, the ethical focus of each intervention, and the original sources. The list is not exhaustive and will be extended in future versions of the thesis to reflect additional case studies and emerging research.

CASE STUDY	TECHNOLOGY USED	ETHICAL FOCUS	SOURCE
Palmyra Arch (Replica 2016-2019)	3D modelling based on documentation, CNC[59] machining of marble	Initial praise as digital rescue archaeology; later critiques for lack of transparency, missing paradata, limited local involvement, symbolic digital colonialism (Stobiecka 2020)	Foley (n.d.); Stobiecka (2020)
Regolini-Galassi tomb	VR + 3D reconstruction	Interpretation + reconstruction	Pietroni & Ferdani (2021)
Ain Fouara statue	Terrestrial Laser Scanning (TLS); 3D point cloud alignment; reverse engineering	Digital preparedness; post-vandalism restoration; institutional responsibility; minimal interpretation	Khodja et al. (2019)
Rosetta Stone	3D scanning and interactive web visualisation (Sketchfab platform	Low contextualisation; reduced auratic experience; limits of affective authenticity in digital surrogates	Cardozo & Papadopoulos (2021)
Landesamt für Denkmalpflege Hessen – integrated 3D documentation programme	Structure from Motion (SfM), handheld structured light scanning, UAV photogrammetry, LiDAR, GigaMesh framework, 3D printing (resin)	Long-term institutional integration; multiscalar approach (objects to landscapes); methodological transparency; documentation quality	Seitz (2022)
Lewis Chess Pieces	3D scanning with rich multimodal integration (text, audio, narrative interface)	Enhanced user experience; affective and epistemic authenticity; importance of narrative embedding	Cardozo & Papadopoulos (2021)
Heritage reconstruction in Aleppo	Not technology-focused; historical and political analysis of conservation/reconstruction across regimes	Colonial and political construction of authenticity; erasure of Islamic-Ottoman heritage; contextualised vs. universal heritage values; dynamic local concepts *(athâr, turâth)*	Lafi (2017)
Kunágota sword	Photogrammetry, 3D modelling, layered virtual restoration (realistic + stylistic modes)	Non-invasive virtual restoration; transparent separation of documentary and hypothetical elements; dual-mode interface for audience engagement	Pietroni & Ferdani (2021)
Palazzo Poggi Museum Digitisation Project (University of Bologna)	Smartphone photogrammetry with colour calibration (Relio 2 light kit, CCP), internal BRDF estimation, post-processing via SHAFT app	Low-cost digitisation for small museums; emphasis on colour fidelity, reproducibility, and accessibility; rigorous testing against laser scanners	Gaiani, Apollonio & Fantini (2020)

[59] Computer Numerical Control. It refers to the use of computer-controlled machines to cut, carve, or mill marble sbased on precise digital instructions.

The Archeomatica Project – Haghia Triada and Polizzello	Open-source 3D modeling in Blender; image-based photogrammetry; interdisciplinary workflows between archaeologists and computer scientists	Knowledge co-production, transparency of modelling decisions, accessible and reproducible workflows, emphasis on virtual reconstruction as cognitive tool	Stanco, Battiato, & Gallo (2011)
Expert system for 3D digitisation method selection (Petrovaradin & Matica srpska)	Rule-based software recommending 3D methods (e.g., photogrammetry + UAV)	Potential over-reliance on algorithmic outputs; dependence on input quality and predefined parameters; lack of stakeholder reflection in system logic	Budak et al. (2019)
Virtual Museums: Hampson & Amarna Projects	High-precision 3D scanning (Konica Minolta VIVID 9i), OBJ models, VRML/X3D, 3D PDF	Emphasis on data provenance, versioning, metadata, reuse; model of long-term accessibility and citation	Limp et al. (2011)
Tutankhamun Tomb Facsimile	High-res 3D scanning, CNC milling, hand-painting	Migration of aura; preservation vs. spectacle; transparency of surrogate	Zalewski (2016); Factum Arte (2014)
Holographic Box of Stories – Mytilene Treasure	Mixed Reality (Pepper's Ghost), interactive storytelling	Balancing aura and immersion; authentic engagement without eclipsing original	Pietroni (2025); Pietroni et al. (2019)
Murcia – Cristo de la Sangre Replica	Photogrammetry, 3D printing	Multisensory access; inclusive authenticity; replica as ethical engagement tool	Garland Thomson (2008); Barack (2016)
Plaster sculpture reconstruction	Photogrammetry, PETG FDM 3D printing, magnetic joints	Reversibility; material compatibility; documentation transparency	Vyhnánková (2023); thesis research
Scan the World	Crowdsourced photogrammetry; online open-access distribution	Digital ownership; open access vs. institutional control; public domain ethics	artec3d.com; ACM (2018)
Nefertiti Hack	Surreptitious photogrammetry + public release	Digital repatriation; colonial power dynamics in digital domain	Nelles & Al-Badri (2016); Wenman (2019)

A Cautionary Case: A Roman Glass Bowl and the Ethics of Material Contrast

While 3D printing offers immense potential for restoration and interpretive reconstruction, not every application yields meaningful or appropriate results. A striking example is found in the case study presented by Aura-Castro et al. (2021), where FDM technology was used to restore a delicate Roman glass bowl by filling in the missing segments with opaque, visibly textured PLA plastic Fig. 12.

Rather than aiding the viewer in imagining the original form, the intervention imposes a stark material and visual dissonance. The 3D-printed components do not emulate the transparency, iridescence, or fragility of Roman glass, and the result is jarring. Far from communicating the aesthetic qualities of the original, the printed fills dominate the artefact's appearance, undermining its historical and material integrity.

This case invites reflection on the ethical implications of such interventions. In particular, it raises questions about:

- Authenticity: Does the 3D addition support the communicative value of the artefact, or does it distort it?
- Material Compatibility: Is the selected filament (PLA) suitable in terms of texture, colour, and reflectivity when juxtaposed with ancient glass?
- Reversibility and Interpretation: Even if technically reversible, does the intervention encourage meaningful interpretation, or confuse it?

There are more sensitive alternatives documented in conservation literature — for example, reconstructions using clear PMMA or resins that better approximate the physical and visual qualities of glass (Barack 2016). In contrast, the solution chosen here appears rushed and aesthetically invasive. The object's aura, as discussed in Chapter 4.3 Aura and Digital Surrogates, is diminished rather than extended.

This example is not presented as a dismissal of FDM technology in conservation. Rather, it serves as a critical reminder that the application of 3D methods must be context-sensitive, aesthetically restrained, and ethically defensible. Restorations are interpretative acts — and as such, they demand not only technical precision, but also visual literacy and curatorial responsibility.



Fig. 12: Reconstructed Roman glass bowl with missing areas filled using opaque white PLA filament and FDM 3D printing. The intervention demonstrates significant material and visual contrast, raising questions about the appropriateness of the technique for fragile archaeological glassware.

5. Long-term Implications

This chapter addresses the long-term implications of integrating 3D technologies into sculptural conservation. It focuses on four interconnected areas: material ageing, the epistemic and curatorial risks of replication, monitoring responsibilities, and institutional accountability. In each section, the ethical dimensions of technical decisions are brought to the foreground.s

5.1. Material Ageing and Stability

The use of synthetic polymers such as PLA, PETG, ABS, and PMMA in conservation has raised serious questions regarding their long-term stability and material compatibility with heritage substrates. These thermoplastics, widely used in FDM 3D printing, offer practical advantages but remain poorly studied under conservation-specific conditions such as UV exposure, humidity, and interaction with porous materials.

Current research by the author at the University of Pardubice explores the chemical interaction between selected polymers and plaster substrates.[60]

Biasiolo's master's thesis, submitted at Ca' Foscari University and the Accademia di Belle Arti di Bologna, highlights the limitations of current polymer evaluation protocols and advocates for cross-disciplinary assessment frameworks grounded in conservation science. Jo and Lee (2020) also note that polymer performance varies widely depending on fabrication parameters and environmental conditions.

The ethical implications of using potentially unstable materials include the risk of physical deterioration, interpretive distortion, and irreversible alteration of historical artefacts. Without established monitoring and reassessment protocols, these risks challenge the principles of minimal intervention and responsible stewardship.

[60] The methods include accelerated ageing (UV exposure and humidity cycles), Oddy testing, Cross-infection testing, Fourier-transform infrared spectroscopy (FTIR), and colourimetric analysis. The focus is on the interaction of PETG, PLA, ABS, and PMMA with plaster.

5.2. The Role of Replication in Conservation Strategy



Fig. 13: Digital model of the Maritime Theatre at Hadrian's Villa. This 3D model was generated through a multi-step digital pipeline integrating laser scanning, photogrammetry, retopology, and semantic segmentation. Designed for virtual anastylosis and interpretative studies, the model exemplifies the potential of interdisciplinary workflows that prioritise both technical precision and archaeological meaning.

3D replication enables new modes of documentation and reconstruction, yet it raises persistent ethical dilemmas regarding authenticity, interpretive transparency, and material substitution. As Koller and Pfarr-Harfst (2018) argue, replicas function not only as technical substitutes but as interpretive instruments that actively shape heritage narratives.

Whether installed in situ or displayed in museums, high-fidelity 3D-printed replicas may blur the line between original and copy. Their legitimacy depends not only on formal accuracy but on how clearly their status is communicated. The Nara Document on Authenticity (1994) expands authenticity to include design, spirit, and context — supporting certain forms of replication — but leaves implementation open to interpretation.

The author's fieldwork shows variation across institutions: while some pursue visible integration and contextual labelling, others prioritise visual unity without critical framing. Such divergences call for transparent decision-making protocols and careful alignment with conservation ethics.

5.3. Monitoring of 3D-printed Additions in Heritage Conservation

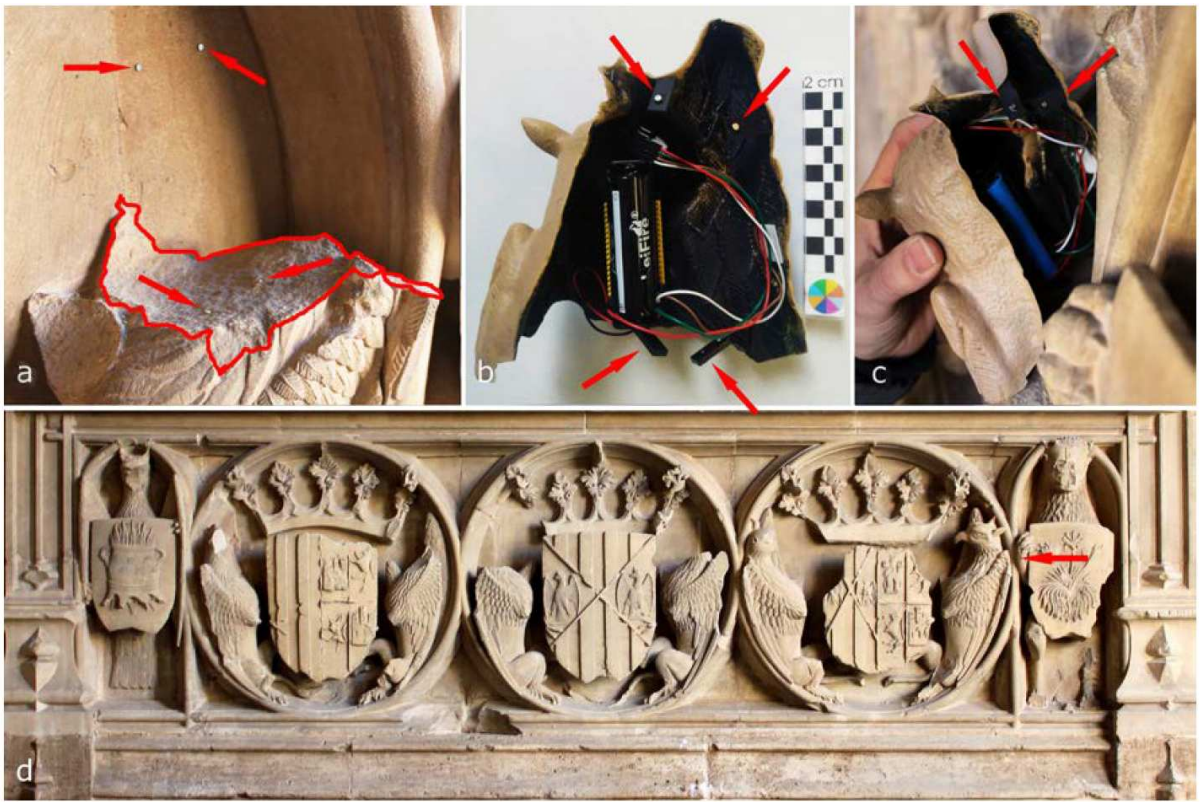


Fig. 14: Installation of the prosthesis into the Tondo of Arms of Castile. An environmental sensor system is located within the interior of the 3D-printed fragment, which is magnetically attached to the sculpture. The intervention is designed to be fully reversible and non-invasive.

While material studies have confirmed the susceptibility of thermoplastics to UV degradation and thermal distortion (San Andrés et al. 2023), most institutions lack standardised procedures for long-term monitoring of 3D additions. This absence is not just procedural but ethical, undermining the principle of accountability.

Best practice suggests adopting a tiered monitoring strategy based on the intended duration and visibility of printed components. For permanent or load-bearing inserts, periodic reassessment should become routine. Examples such as the Landesamt für Archäologie Sachsen show how digital methods can support non-invasive monitoring over time (Reuter, Elburg, and Innerhofer 2014). (See Fig. 14).

Hermon, Sugimoto, and Mara (2007) advocate for embedding documentation and metadata within institutional protocols, echoing the London Charter's emphasis on transparency and traceability. Without such systems, printed additions risk becoming untraceable interventions — counter to the ethics of verifiability and reversibility.

5.4. Digital Preservation and Institutional Responsibility

Digital preservation is not merely a technical issue but a core ethical responsibility. R eleasing scans without governance can sever them from their cultural context.[61] Immonen and Malinen (2020) further demonstrate how platform dependency and insufficient metadata expose digital collections to decay and misinterpretation.

Institutions like the Smithsonian have implemented structured metadata and paradata frameworks that serve as exemplary models. These include descriptive, technical, and curatorial records tied to each 3D asset. Despite such models, uptake remains limited, particularly in underfunded settings. As the European Commission (2020) underscores, digitisation without sustainability planning is an ethical failure.

The FAIR and CARE principles offer guidance.[62] Yet their institutional adoption has been uneven. Many institutions treat file upload as synonymous with preservation, a conflation that invites loss.

An increasingly urgent issue is platform dependency on third-party hosting platforms.[63] Best practice, as adopted by several leading institutions, involves separating archival storage (institution-controlled) from public access layers.

Emerging mechanisms such as NFTs introduce further ethical risks.[64] Without clear protocols, digital surrogates of heritage objects may be monetised or misused. Cronin (2015) calls for intellectual repatriation frameworks to protect cultural data, warning against abstraction of heritage into decontextualised assets.

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[61] See Ad Hoc Museum Collective (2019) for a discussion on how unregulated digitisation contributes to the detachment of digital assets from their interpretive and community anchors.

[62] FAIR: Findable, Accessible, Interoperable, Reusable. CARE: Collective Benefit, Authority to Control, Responsibility, Ethics. While FAIR emphasises technical interoperability, CARE addresses ethical governance, particularly for Indigenous and community-based data.

[63] Examples include Sketchfab and Google Arts & Culture. These platforms provide wide visibility but do not guarantee long-term preservation or institutional control.

[64] Non-fungible tokens (NFTs) allow for the monetisation of unique digital assets. When applied to cultural heritage surrogates, they may abstract and privatise communal or sacred knowledge unless clearly governed.

Tab. 2 Overview of selected online platforms used for sharing and publishing 3D digitised cultural heritage. This table is loosely based on the listing provided in Appendix 2 of Emma Cieslik's *3D Digitization in Cultural Heritage Institutions Guidebook (2020),* but has been updated and expanded to reflect the landscape as of 2025. It includes both well-established and emerging platforms, focusing on those most relevant for public access, educational use, and institutional engagement. The list is not exhaustive and does not include certain specialised repositories such as MorphoSource[65] or Share3D[66]. As the cultural heritage sector continues to embrace digitisation, the number and diversity of such platforms are rapidly growing. Credits: Emma Cieslik, 2020, original compilation in Appendix 2: Commercial Online Viewers for Cultural Heritage 3D Models.

PLATFORM	3D VIEWING	EDUCATIONAL USE POLICY	DESCRIPTION OF 3D PLATFORM	WEBSITE
Thingiverse	Yes	CC licenses and institutional licenses	This platform is dedicated to sharing user-created digital design files. All models on this website are free to download. This platform is useful for 3D printing (Johnson et al. 2017).	https://www.thingiverse.com
Sketchfab	Yes	Institution-specific license	This platform supports the upload, publication, and visualization of 3D models on the web and supports the inclusion of 3D content in standard web pages and social media. This is the most commonly used viewer for cultural heritage content.	https://sketchfab.com
MyMiniFactory	Yes	Varies by model; includes both proprietary and Creative Commons licenses	This platform houses 3D models that can be purchased. This website also houses the models for the Scan the World project, and asking all uploaders if they are Scan the World affiliated.	https://www.myminifactory.com/scantheworld
3D Heritage Online Presenter (3DHOP)	Yes (limited interactivity)	Google Terms of Use	This platform is more flexible than Sketchfab in supporting more presentation and interaction modes. 3DHOP is based on the SpiderGL library, implementing plug-free free 3D rendering on web browsers.	https://3dhop.net
Smithsonian 3D Digitization	Yes (primarily 2D content)	Europeana Terms of Use	This platform allows for models to live on the cloud, meaning that it runs on all modern web browsers without requiring a plug-in to download. This platform allows 3D models to be taken on tablets or mobile devices but only accepts OBJ uploads.	https://3d.si.edu
Universal Viewer	Yes	CC-BY	This is an open source platform to allow sharing 3D content. The benefit to this website is that it is zoomable, embeddable, extensible (supporting 3D), and securable, allowing content to be password protected.	https://universalviewer.io
Google Arts&Culture	Yes	No explicit policy; use under GPL/LGPL	This platform allows for the upload of 3D objects on the web. This platform also houses virtual reality products, Tilt Brush and Blacks. Many of the objects have low-polygon style, which fits with Google's Daydream platform which allows it to run more efficiently if the object is less complex.	https://artsandculture.google.com
Europeana	Yes (primarily 2D content; limited 3D interactivity)	Europeana Terms of Use	Metadata-rich cultural heritage aggregator operated by the Europeana Foundation. While its primary focus is 2D content, it does support basic 3D object viewing. Not a dedicated 3D platform, but valuable for access to digitised heritage content from a wide range of European institutions.	https://www.europeana.eu
CyArk	Yes	Varies by project; generally open for educational use with attribution	CyArk is a non-profit organisation dedicated to the digital preservation of cultural heritage sites worldwide. Using technologies such as laser scanning, photogrammetry, and 3D modelling, it creates highly accurate and detailed digital records of heritage sites at risk. The platform offers public access to many of its 3D visualisations and educational resources, and frequently collaborates with local communities, government bodies, and UNESCO.	https://www.cyark.org
Threeding	Yes	Varies by model; includes both proprietary and Creative Commons licenses	Threeding is a commercial platform for buying, selling, and sharing 3D printable models. It collaborates with museums and cultural institutions to digitise and distribute cultural heritage artefacts. Some models are offered for educational and non-commercial use under open licenses.	https://www.threeding.com
Rekrei (formerly Project Mosul)	Yes	Open access for educational and heritage awareness purposes	Rekrei is a volunteer-driven initiative aimed at reconstructing lost or destroyed heritage through crowdsourced photographs. The platform uses photogrammetry to create 3D models of artefacts destroyed in conflict zones, often in collaboration with cultural heritage professionals and institutions.	https://rekrei.org

[65] https://www.morphosource.org

[66] https://share3d.com

Ancient Art Archive	Yes	Educational access encouraged; subject to project-specific terms	Ancient Art Archive documents and shares high-resolution 3D and immersive imagery of prehistoric art, including cave paintings and rock carvings. Their goal is to preserve and promote ancient art through digital storytelling and scholarly research.	https://www.ancientartarchive.org
OpenHeritage3D	Yes	Open access with scholarly metadata	Peer-curated public repository maintained by CHEI (UC San Diego).	https://www.openheritage3d.org

By integrating ethical foresight with technical expertise, institutions can transform digital preservation from an afterthought into a central pillar of heritage stewardship. This chapter argues that the longevity and ethical integrity of digital surrogates must be planned from the outset — only then can the promise of 3D conservation be fulfilled responsibly.

6. Practical Guidelines

This chapter synthesises key considerations from the preceding theoretical and analytical discussions into a set of practical guidelines for implementing 3D technologies in sculpture conservation and cultural heritage. The aim is to help conservators, curators, and heritage professionals apply 3D technologies responsibly — without compromising core conservation principles. Recommendations draw on international charters (London Charter, UNESCO 2003), FAIR and CARE principles, published case studies, and the author's own conservation practice.[67]

6.1. Purpose and Scope Definition

Before initiating any 3D-related intervention, define the purpose and long-term intent. Whether for documentation, exhibition, restoration, or education, the goal must be clearly stated and reflected in the workflow. This clarity avoids ethical drift — for example, when a scan intended for documentation is later used for irreversible restoration.

Recommendation: Use project scoping documents that specify goals, allowable uses, and interpretive context from the outset. Ensure team consensus and stakeholder understanding.

6.2. Material Compatibility and Reversibility

Choice of materials must align with the principles of minimal intervention and reversibility. Research shows variable ageing behaviours in PLA, PETG, ABS, and PMMA, including yellowing, embrittlement, or chemical instability under UV or thermal stress.

Recommendation: Prioritise materials with known stability under heritage-specific conditions. Avoid strong adhesives. Use mechanical or reversible attachments (e.g. magnets, clips). Document all material choices in the conservation record.

6.3. Transparency in Representation

3D models and printed replicas must not mislead viewers. High-fidelity outputs risk creating an illusion of authenticity.

[67] These guidelines are informed by interdisciplinary literature, including Cieslik (2020), Di Giuseppantonio Di Franco et al. (2018, 2015), Cardozo and Papadopoulos (2021), and ethical frameworks such as the London Charter and Seville Principles.

Recommendation: Clearly differentiate digital or printed additions through visual cues, metadata, or interpretive labels. Maintain paradata (documentation of modelling and decision processes). Align with London Charter's emphasis on epistemic transparency.

6.4. Intellectual and Cultural Ownership

Digitisation does not override ethical obligations toward source communities or stakeholder groups. Even public-domain objects may carry cultural sensitivities.

Recommendation: Engage communities in digitisation projects where appropriate. Avoid sharing culturally sensitive models without consent. Use open licences with clear terms (e.g. Creative Commons BY-NC) and contextual metadata. Adopt CARE principles when applicable.

6.5. Participatory and Inclusive Practice

Effective 3D conservation practices benefit from the involvement of community members, local experts, or artists. Participatory processes enrich interpretation, build trust, and mitigate ethical blind spots.

Recommendation: Incorporate feedback loops and co-curation opportunities in digitisation workflows. Invite community review of models before public display or dissemination.

6.6. Digital Preservation Planning

A 3D model is not a static output — it requires care over time. Without robust digital preservation, even well-made assets risk obsolescence or misinterpretation.

Recommendation:

- Use open, well-documented formats (OBJ, PLY, STL).
- Create structured metadata and paradata.
- Integrate 3D files into conservation records.
- Adopt institutional policies for periodic data migration, integrity checks, and archival storage.

These six principles support a pragmatic, ethics-driven use of 3D technologies. They encourage careful planning, humility in interpretation, and sustained institutional commitment. Digital innovation should serve the values of conservation — not replace them.

3D tools expand what is possible in sculpture conservation, but their ethical deployment depends on clarity, transparency, consent, and stewardship. This framework helps practitioners navigate complexity with confidence and care.

Summary

This thesis investigated the ethical implications of using 3D technologies — such as photogrammetry, digital modelling, and additive manufacturing — in the conservation of sculptures. The research focused on how these technologies interact with established conservation values, including authenticity, reversibility, and material compatibility.

A review of international frameworks, including the Venice Charter, London Charter, Seville Principles, and UNESCO guidelines, revealed that while these documents provide ethical foundations for digital heritage practices, they often lack enforceability and fail to address long-term material risks. The thesis argued that ethical guidance must evolve to reflect the hybrid nature of digital–material interventions.

Case studies involving both virtual surrogates and 3D-printed reconstructions highlighted the interpretive and material challenges posed by these tools. Attention was given to how replicas may affect public perception, particularly in sacred or culturally sensitive contexts, and to the practical risks of introducing polymer-based materials into historical settings.

In response, a set of practical guidelines was developed to support transparent, reversible, and context-aware applications of 3D technologies in conservation. These recommendations stressed the need for interdisciplinary collaboration, critical evaluation, and long-term responsibility. The study concluded that integrating 3D technologies into conservation practice requires a rearticulation of existing ethics, rather than the invention of new ones.

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Conclusion

The integration of 3D technologies into sculpture conservation represents not a break from tradition, but rather a contemporary extension of long-standing ethical and theoretical concerns. Issues such as authenticity, reversibility, and material compatibility — long central to the conservation discourse — reappear in new form when applied to digital–material hybrids. As early as the Venice Charter (1964), the dilemmas surrounding material additions and aesthetic coherence were clearly articulated. These debates remain highly relevant in the age of polymers and virtual models. In this sense, nothing is entirely new — only the material context has shifted.

This thesis has demonstrated that 3D scanning, modelling, and additive manufacturing expand the scope of conservation interventions while simultaneously destabilising core values. A close reading of international charters and ethical frameworks — such as the London Charter, Seville Principles, and ICOM Code of Ethics — shows that current guidelines offer foundational principles for transparency, paradata, and accountability. However, these documents lack binding authority and do not yet provide robust material protocols. Notably, documents produced by UNESCO in 2003 and 2009 remain under-implemented, revealing a persistent gap between theory and practice.

Ethical challenges are not limited to the digital domain. Additive manufacturing introduces materials whose ageing properties, removability, and chemical interactions with substrates are often insufficiently understood. As this research has shown, even chemically stable polymers such as PETG and PLA can raise critical concerns in conservation contexts. Case studies discussed in Chapters 5 and 6 confirm that well-intentioned uses of these materials — along with unknown adhesives and evolving print qualities — have shown visible limitations in terms of adhesion, surface compatibility, and long-term stability. These risks are not purely technical — they are deeply ethical, as they touch on the very concepts of permanence, trust, and responsible stewardship.

The blurred boundary between original and replica also remains problematic. Concepts such as aura migration, curated authenticity, and epistemic transparency show that replicas are never neutral. Whether virtual, tactile, or hybrid, they must be clearly contextualised. Otherwise, they risk misleading viewers and undermining interpretive clarity. This is particularly important in sacred or culturally sensitive contexts, where the replication of artefacts may unintentionally conflict with spiritual meanings or community expectations. The ethical burden lies not only in material accuracy, but in shaping the public experience with honesty and care.

Some institutions have begun to respond to these challenges through participatory models of digitisation, inviting communities to define how their heritage is represented. These shifts signal a broader transformation in conservation ethics — from technical problem-solving toward relational accountability and shared authorship. As discussed in Chapter 3.4 - Emerging Frameworks and European Initiatives, this realignment calls for an ethics of care as much as an ethics of precision.

Chapter 6 - Practical Guidelines has proposed a framework of practical guidelines, treating digital interventions not as neutral tools but as interpretive acts embedded in institutional, cultural, and material contexts. Transparent documentation, reversible attachment, participatory validation, and rigorous material testing emerge as the cornerstones of responsible practice. This approach calls for conservation to embrace both continuity with its past and responsiveness to contemporary demands.

Ultimately, the thesis argues that digital technologies should not be viewed as a rupture in conservation ethics, but as a lens through which foundational principles are reinterpreted. The ethical imperative lies in navigating this reinterpretation with awareness, caution, and scholarly depth. Professional conservators must not surrender ethical judgement to technological novelty, nor rely on outdated models that ignore digital realities. Instead, they must critically assess the tools at their disposal and remain accountable — both to material heritage and to its cultural meaning.

This work draws upon the author’s own sustained engagement with the topic since 2022, including a bachelor’s thesis on 3D printing in plaster conservation, ongoing material testing in a second master’s thesis, and recently published article on ethical and technological aspects of implementige 3D technologies in sculpture conservation in JAIC. It seeks not only to map existing ethical terrain, but also to sharpen the discourse and open new questions.

Areas for Further Research

Several open questions remain. How can standardised reassessment protocols for 3D materials be developed? What legal and ethical frameworks will govern digital surrogates when they themselves become heritage? Can the public be more actively involved in co-authoring digital replicas without undermining scholarly integrity? What are the long-term implications of data obsolescence and digital decay for conservation institutions? These questions exceed the scope of this thesis but are crucial for the future of responsible digital heritage practice.

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Disclosure of AI Tool Use in This Thesis

AI TOOL USED	**FUNCTION**	**AFFECTED SECTIONS**	**REMARKS**
DeepL Translator	Translation of German/Italian literarture sources.	Entire thesis (as needed).	All translations were critically reviewed and revised manually.
ChatGPT 4.0 (OpenAI)	Rephrasing of draft paragraphs.	Chapter 4.1.	Used for terminology suggestions only; all arguments are author-constructed.
ChatGPT 4.0 (OpenAI)	Deep research tool for broadening the research of the literature.	Chapter 3 and 4.	Suggestions from ChatGPT were edited and validated against source content.
ChatGPT 4.0 (OpenAI)	Generating clearly structured tables in spreadsheet format (.csv or .xlsx), based on research data I provided.	Chapter 3.7 and 5.4.	The generated tables serve to organise, summarise, or present complex information in a more accessible form.
ChatGPT 4.0 (OpenAI)	Refining English academic phrasing.	As needed.	

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List of Tables

Tab. 1: Selected case studies illustrating the ethical dimensions of 3D technologies in cultural heritage practice. The table summarises examples discussed throughout the thesis, noting the technological methods used, the ethical focus of each intervention, and the original sources. The list is not exhaustive and will be extended in future versions of the thesis to reflect additional case studies and emerging research. 49

Tab. 2 Overview of selected online platforms used for sharing and publishing 3D digitised cultural heritage. This table is loosely based on the listing provided in Appendix 2 of Emma Cieslik's *3D Digitization in Cultural Heritage Institutions Guidebook (2020),* but has been updated and expanded to reflect the landscape as of 2025. It includes both well-established and emerging platforms, focusing on those most relevant for public access, educational use, and institutional engagement. The list is not exhaustive and does not include certain specialised repositories such as MorphoSource or Share3D. As the cultural heritage sector continues to embrace digitisation, the number and diversity of such platforms are rapidly growing. Credits: Emma Cieslik, 2020, original compilation in Appendix 2: Commercial Online Viewers for Cultural Heritage 3D Models. 56

Tab. 3 Overview of Digitisation Platforms and Repositories (adapted from Cieslik 2020). This table is based on Appendix 1: Current Museum Digitization Projects, Digitization Labs, and Independent Digitization Projects from Emma Cieslik's 2020 *3D Digitization in Cultural Heritage Institutions Guidebook* (pp. 68-74). It presents a broad typology of institutional, governmental, and independent initiatives focused on 3D digitisation in the cultural heritage sector.This work serves as a comparative reference for the updated landscape discussed throughout the main chapters of this thesis (see Tab. 2). 83

Tab. 4 Overview of Online Platforms for Sharing and Presenting 3D Cultural Heritage Models (adapted directly from Cieslik 2020) This table is based on Emma Cieslik's *3D Digitization in Cultural Heritage Institutions: A Guidebook,* 2020, Dr. Samuel D. Harris National Museum of Dentistry. Appendix 2, pages 74–75. It reflects the state of 3D platforms as of 2020. Further above in this thesis (see Tab. 2) an updated list of platforms has been compiled to reflect developments over the past five years. The present table builds on Cieslik's work and extends it with current data up to 2025, with a particular focus on open-access repositories, sustainable formats, and institutional infrastructure.....87

Appendix 1: Extended Glossary

This appendix expands on key terminology mentioned in the thesis, to be found in Chapter 1 - Key Terms. It includes technical definitions used in digital heritage literature.

Cognitive Interaction
A design principle in digital heritage experiences focused on enhancing users' understanding through interactive engagement. It moves beyond passive viewing, allowing users to actively explore, compare, and interpret reconstructed content. (Pietroni & Ferdani 2021).

Digital Twin
A data-rich 3D model replicating both the structure and dynamic behaviours of a physical object, often used in monitoring and simulation.

Digitalisation
The integration of digital tools into institutional practice, including metadata, access platforms, and workflows (Liao, Zhao, and Sun 2020).

Digitisation
The technical process of converting physical artefacts into digital form, typically via 2D or 3D scanning (Liao, Zhao, and Sun 2020).

Extended Matrix (EM)
A stratigraphic model developed for digital archaeology. It records the origin, transformation, and interpretative status of each component within a reconstruction, ensuring methodological transparency and traceability. (Pietroni & Ferdani 2021).

Fixity
Fixity refers to the property of a digital object to remain unchanged over time. It is verified using checksums or cryptographic hashes, and is essential for confirming that no data corruption or unauthorised alteration has occurred. (Digital Preservation Coalition 2023a)

Light-Dependent Digitisation
Digitisation using projected or reflected light, including techniques like structured light scanning, sensitive to ambient conditions (Cieslik 2020).

Numinous Object

A heritage object perceived as spiritually or emotionally powerful. Such objects evoke reverence, awe, or a personal connection to the past in viewers. The concept draws on Rudolf Otto's notion of *numen* and has been explored in heritage studies as a key factor influencing visitor motivation and interpretative design. (Cameron and Gatewood 2000).

Philological Reconstruction

A reconstruction method grounded in critical historical, iconographic, and stylistic evidence. It prioritises traceable, transparent interpretation over speculative visualisation, aiming to preserve the scholarly rigour of digital heritage outputs. (Pietroni & Ferdani 2021).

Photogrammetry

A method of producing 3D models from overlapping photographs, widely used in conservation due to its accessibility and non-invasiveness (Cieslik 2020).

Reflectance Transformation Imaging (RTI)

Captures how an object's surface reflects light from different angles, revealing subtle surface details (Cieslik 2020).

Significant properties

Significant properties are those characteristics of a digital object that must be preserved for it to remain authentic, usable, and meaningful over time. These may include visual appearance, structure, interactivity, or embedded metadata. (Digital Preservation Coalition 2023a)

Structure from Motion (SfM)

A photogrammetric technique that reconstructs 3D geometry by tracking the movement of the camera across multiple overlapping images taken from different viewpoints. SfM is widely used in cultural heritage documentation due to its portability, low cost, and non-contact nature (Westoby et al. 2012).

Virtual Archaeology

The use of 3D modelling and simulation technologies to support archaeological interpretation, research, and public engagement. It enables the reconstruction of archaeological sites, artefacts, and contexts in virtual environments, often to test hypotheses, visualise past landscapes, or offer educational experiences. Originally defined by Reilly (1991) as the use of digital surrogates for archaeological formations, the term has since evolved to encompass

immersive, interactive tools in cognitive and experimental archaeology (Stanco, Battiato, and Gallo 2011).

Appendix 2: Commercial Online Viewers for Cultural Heritage 3D Models

The following table is reproduced verbatim from *3D Digitization in Cultural Heritage Institutions: A Guidebook* by Emma Cieslik (2020), Appendix 1, pages 68-74. It provides a snapshot of the most widely used commercial platforms for viewing, embedding, and disseminating 3D cultural heritage content as of mid-2020. All textual content in the table has been retained without alteration. However, given the five-year gap since publication, several of the platform URLs or functionalities have changed; where applicable, hyperlinks have been updated for current accessibility. A more recent overview of available platforms and tools can be found earlier in this thesis (see Tab. 2), which extends and contextualises this dataset to reflect developments as of 2025.

Tab. 3 Overview of Digitisation Platforms and Repositories (adapted from Cieslik 2020). This table is based on Appendix 1: Current Museum Digitization Projects, Digitization Labs, and Independent Digitization Projects from Emma Cieslik's 2020 *3D Digitization in Cultural Heritage Institutions Guidebook* (pp. 68-74). It presents a broad typology of institutional, governmental, and independent initiatives focused on 3D digitisation in the cultural heritage sector.This work serves as a comparative reference for the updated landscape discussed throughout the main chapters of this thesis (see Tab. 2).

NAME OF INSTITUTION	INFORMATION ABOUT INSTITUTION	EXAMPLE
Smithsonian Institution *Washington, D.C., United States*	The Smithsonian Institution Digitization Office focuses on the development of 3D models to share through three-dimensional technology and analysis tools. The office partners with all Smithsonian museums. Some, but not all, of the 3D models on their website are open access.[68] This website also offers features to change the material of the object on the x, y, or z axis to visualize thismobject with an autopsy view.[69] These models are housed on the Smithsonian viewer.	Mammuthus primigenius (Blumbach) https://3d.si.edu/object/3d/mammuthus-primigeniusblumbach:341c96cd-f967-4540-8ed1-d3fc56d31f12 (Accessed on 20. 05. 2025) Embedded viewer
Metropolitan Museum of Art *New York, New York, United States*	The Met has worked to start digitizing 5 collections of objects. The Met MediaLab has been using photogrammetry and hand-held 3D scanners to render objects. In 2017, the Met launched the Open Access Initiative, making 375,000 images available under the Creative Common Zero code. All 3D scans have been uploaded to the MakerBot Thingiverse Platform. The Met's public data set was also added to Google's BigQuery platform.[70]	Nydia, The Blind Flower Girl of Pompeii (1853-1854), by Randolph Rogers https://www.thingiverse.com/thing:24089 (Accessed on 20. 05. 2025) Thingiverse website
The British Museum *London, England, United Kingdom*	The British Museum has created 14 3D models of busts, statues, and sarcophagi from its collection that can be downloaded from Sketchfab and printed at home. Some of these models have embedded audio descriptions or can be viewed on a virtual reality device as well. The models also contain additional preservation metadata.[71]	Lewis Chess Set from Trondheim, Norway (1150-1200) https://sketchfab.com/3d-models/lewis-chess-set-eddbebab12424c8aa610a21b9b7e19e5 (Accessed on 20. 05. 2025) Sketchfab website

[68] Open access means that the user can download, modify, and share the 3D model of the Smithsonian object for any purpose. This specific characteristic is designated by the Creative Commons Zero (CC0) code by the model on the website.

[69] https://3d.si.edu (Accessed on 20. 05. 2025)

[70] https://www.thingiverse.com/met/designs (Accessed on 20. 05. 2025)

[71] https://sketchfab.com/britishmuseum (Accessed on 20. 05. 2025)

The British Library *London, England, United Kingdom*	The British Library, along with funding from the Polonsky Foundation, has digitized 1,275 Hebrew manuscripts under the Hebrew Manuscript Digitisation Project (2013-2016). The manuscripts were digitized with photogrammetry to produce 3D models. The 3D models were published to Sketchfab.[72]	Pentatech with the Five Scrolls, Psalms, Job, and Haftarot, Italy, 1486 https://sketchfab.com/3d-models/pentateuch-add-ms-4709-d6ca51e05b9a4d52b6dc6092cb71093f (Accessed on 20. 05. 2025) Sketchfab website
Guimet Museum *Paris, France*	Most of the objects from the Guimet Museum that are digitized are housed on MyMiniFactory and were scanned as part of the Scan the World project. On MyMiniFactory, each model contains a description about the object and its background, including the example which was made during the Song Dynasty.[73]	Bodhisattva statue of Avalokitesvara, https://www.myminifactory.com/object/3d-print-bodhisattva-avalokitesvara-potalaka-at-the-guimet-museum-paris-6336 (Accessed on 20. 05. 2025) MyMiniFactory website
Museum für Naturkunde *Berlin, Germany*	This natural history museum has created a 3D scanner for digitizing the insect collection. The Darmstadt Insect Scanner (DISC3D), can digitally image the smallest insects into high-resolution, 3D objects. This opens access to insect collections to researchers across the world. By 2030, all 300 million objects in the museum will be digitally recorded. The collection is also housed on Sketchfab.[74]	Graphosoma lineatum insect https://sketchfab.com/3d-models/graphosoma-lineatum-59fa16902b924d26bde9e626c76bb28d (Accessed on 20. 05. 2025) Sketchfab website
Illinois Library: Sousa Archives *Champaign, Illinois, United States*	The Sousa Archives contains the Music Instrument and Digital Image and 3D Model collection contains instruments dated between 1810 and 1972. Each set of images includes the provenance of the instrument. The database contains high resolution 3D still images of the front, back, side, top and bottom of each instrument and 3D digital models.[75]	Antoniophone https://digital.library.illinois.edu/items/9836e220-ea50-0134-23c2-0050569601ca-8#?cv=0&r=0&xywh=-1337%2C-48%2C4929%2C4787 (Accessed on 20. 05. 2025) Embedded viewer
University of Michigan Museum of Paleontology *Ann Arbor, Michigan, United States*	This University of Michigan Online Repository of Fossils was established to increase accessibility to fossil specimens through online 3D and 2D representations, including 3D invertebrates and 3D vertebrates.[76]	Specimen UMMP VP 55037 (Dimetrodon composite skeleton) https://umorf.ummp.lsa.umich.edu/wp/wp-content/3d/viewer.html?name=1401&extension=ctm (Accessed on 20. 05. 2025) Embedded Viewer
Royal Belgian Museum of Natural Sciences *Brussels, Belgium*	This natural history museum houses 38 million specimens, including entomology, anthropology, paleontology, and geology. The museum uses structured light scanning Mesh Scan to digitize objects. For delivery of the finalized 3D	Skull excavated from Spy Cave, Lohest (1885-1886) https://virtualcollections.naturalsciences.be/virtual-collections/anthropology-prehistory/anthropology/neandertals/spy/spy-1-skull

[72] https://www.bl.uk (Accessed on 20. 05. 2025)

[73] https://www.myminifactory.com/search#/?{%22searchString%22:%22guimet%20museum%22} (Accessed on 20. 05. 2025)

[74] https://www.museumfuernaturkunde.berlin/en/museum/media/press/a-collection-opens-live-digitization-insects-exhibition (Accessed on 20. 05. 2025)

[75] https://digital.library.illinois.edu/collections/fe824900-6c8d-0134-1e34-0050569601ca-b (Accessed on 20. 05. 2025)

[76] https://umorf.ummp.lsa.umich.edu/wp/ (Accessed on 20. 05. 2025)

	models, a Sketchfab iFrame is embedded on a webpage of the virtual museum.[77]	(Accessed on 20. 05. 2025) Embedded Viewer
Barcelona Natural History Museum *Barcelona, Spain*	The Barcelona Natural History Museum houses BioExplore, an online catalogue of 3D models including specimens not often on display. This 3D portal also includes an explanation describing the organism's place in the collections and linking them to the natural environment. The 3D models are embedded into the museum website in a Sketchfab viewer.	Crocuta crocuta (spotted hyena) skull https://www.bioexplora.cat/en/osteologic-atlas/mzb_2002-0873/32 (Accessed on 20. 05. 2025) Embedded Sketchfab Viewer
Harvard Museum of the Ancient Near East *Cambridge, Massachusetts, United States*	The Harvard Museum of the Ancient Near East is home to Near East archaeological artifacts. These artifacts include cylinder seals, sculpture, coins, and cuneiform tablets. The Harvard Museum has enabled users to engage with objects in the collection through 3D models on Sketchfab and on viewers embedded in the website.[78]	Coffin of Anku-Khonsu (includes animation) https://sketchfab.com/3d-models/coffin-of-ankh-khonsu-6132b52aa5904b1dbdd631235fc52c66 (Accessed on 20. 05. 2025) Embedded Sketchfab Viewer
3D DIGITIZATION LABORATORIES		
Virtual World Heritage Lab	This laboratory is based at the Indiana University School of Informatics and Computing.[79] The focus of this lab's investigations include 3D scientific simulations of spaces and cultural heritage objects. This lab conducted the Uffizi Digitization Project, the Digital Hadrian's Villa Project, and the Digital Atzompa Project.	Digital reconstruction of Hadrian's villa https://projects.idialab.org/HVWebGL/ Accessed on 20. 05. 2025) Embedded Viewer
Competence CenterCultral Heritage Digitization Lab	This laboratory is based at the Fraunhofer Institute for Computer Graphics Research IGD. This lab works to create true-to-original 3D representations with accuracy down to the micrometer level. The 3D data gained serves for quality control, reconstructions, or surface reconstructions. This lab is working on the first autonomous 3D scanning pipeline.[80]	Helmet of the Lord of Morken (around 600 AD) https://cultlab3d.de/index.php/helmet/ (Accessed on 20. 05. 2025) Embedded Viewer
Factum Foundation	This research center in Londonworks is focused on recording, process, outputs, and experimenting with techniques. This lab actively works with photogrammetry, Lucida 3D scanning, panoramic photography, LiDAR scanning, structured or white light scanning, and Veronica Chorographic Scanner.[81]	Lamentation over the Dead Christ (1463), by Niccolò dell'Arca https://factumfoundation.org/our-projects/3d-sculpting/archive-analysis-and-recording-of-cultural-heritage-in-venice/niccolo-dellarcas-lamentation-over-the-dead-christ/ (Accessed on 20. 05. 2025) Descriptive video
3D DIGITIZATION PROJECTS		
3D Icons Project	The EU Icons Ireland, part of 3D Icons, digitized 130 monuments and buildings across England to provide this data online. This project has digitized 130 monuments and buildings from Ireland, including decorated high crosses, the island monastery of Skellig Michael, and more.	Clones High Cross https://sketchfab.com/3d-models/clones-high-cross-190e52cb659f4cbb98dd672d2d18a210 (Accessed on 20. 05. 2025)

[77] https://www.naturalsciences.be (Accessed on 20. 05. 2025)

[78] https://hmane.harvard.edu/3d-models (Accessed on 20. 05. 2025)

[79] https://vwhl.luddy.indiana.edu/index.html (Accessed on 20. 05. 2025)

[80] https://www.igd.fraunhofer.de/de/branchen/kultur-und-kreativ/3d-scanning.html#home (Accessed on 20. 05. 2025)

[81] https://factumfoundation.org (Accessed on 20. 05. 2025)

		Sketchfab website
Scan the World Project	This project, started in June 2014, is a cultural heritage community-based project to share 3D printable sculptures and artifacts. This project has already scanned 16,173 objects in 790 places around the world. This project addresses the need for museums to have 3D data of their artifacts accessible or downloadable to the public. This project also creates 3D-printable models for the partially-sighted. This website downloadable 3D models are housed on MyMiniFactory.[82]	David (1501-1504), by Michangelo https://www.myminifactory.com/object/3d-print-michelangelo-s-david-in-florence-italy-2052 (Accessed on 20. 05. 2025) MyMiniFactory
MayaCityBuilder	This project uses procedural modelling to produce 3D visualizations of Ancient Maya cityscapes. As part of this project, the WebGL application also contains information and images related to the ceramic topologies that were used for the architecture, including the variety of the specific types of ceramic and what it was used form.	MayaCityBuilder https://mayacitybuilder.org (Accessed on 20. 05. 2025) Embedded viewer
The Scottish Ten	This project, started in 2009, works to document Scotland's world heritage sites and other international heritage sites to create 3D data related to their conservation and management, interpretation, and visual access. The project was conducted by Historic Environment Scotland and the Glasgow School of Art's School of Simulation and Visualization with CyArk.[83]	Marshawn Chambered Cairn, Orkney, Scotland https://www.youtube.com/watch?v=_DX-OBFdUTE (Accessed on 20. 05. 2025) Descriptive video
The Virtual Amarna ProjecT	This project involved the digitization of the Egyptian site of Amarna using a Konica Minolta Vivid 9i triangulation laser scanner, and these 3D scans are now held in the Virtual Amarna Museums. Some of the scanned objects were used as part of the LEAP II project and were part of the Archaeology Data Service Archive.	Wooden Egyptian artifact https://archaeologydataservice.ac.uk/archives/view/amarna_leap_2011/downloads.cfm?obj=yes&obj_id=5239&CFID=d3f0ff48-d5d4-4fda-a346-6827090a0c2e&CFTOKEN=0 (Accessed on 20. 05. 2025) Downloadable mesh
The Uffizi Digitization Project	This project was conducted by the VIrtual World Heritage Laboratory, the Politecnico di Milano, and the University of Florence to digitize the complete collection of Greek and Roan sculpture in the Uffizi, Pitti Palace, and Boboli Gardens. The statues include works of Greek and Roman art.	Medici Venus (1 CE), by Kleomenes, son of Apollodorus http://www.digitalsculpture.org/florence/main/model/31df125d63b747af841d8fca4eb7b8f8 (Accessed on 20. 05. 2025) Embedded Sketchfab viewer
Connecting Early Medieval European Collections Project	This is an EU-funded cooperation project focused on Connecting Early Medieval European Collections (CEMEC) to create a collaborative network and cost-effective business model. Drawing on objects in the participating museums, the project curated "Crossroads," a travelling exhibition focused on connectivity and cultural exchange during the Early Middle Ages (300-1000) in Europe.	Box Broach https://sketchfab.com/3d-models/box-brooch-dobozfibula-dunapataj-86dc26bdff474e0bb90537509be0c23d (Accessed on 20. 05. 2025) Sketchfab website
New Zealand Digital Library Project	The 3D Digital Archive of the Future was a project created in collaboration with Victoria University of Wellington and the National Library of New Zealand, exploring the use of 3D media in libraries. The project focused on three goals related to engaging the public with WWI: (1) 3D animation of a WWI photograph, (2) 3D printing as a reference image for educational and contextual media, (3) and augmented reality through 3D modelled objects.	3D printing exploring artist Paul Jenden https://natlib.govt.nz/blog/posts/the-digital-archive-of-the-future (Accessed on 20. 05. 2025) Descriptive article
Florence As It was: the	This digital project works to reconstruct the city of Florence in the way in which it appeared in the 15th century. Through visualized models, visitors can inspect, tour, and visit the	Orsanmichele building https://www.google.com/search?client=safari&rls=en&q=florenc

[82] https://www.myminifactory.com/scantheworld/ (Accessed on 20. 05. 2025)

[83] CyArk is a non-profit organization founded in 2003 to digitally record, archive, and share cultural heritage sites across the world, specifically addressing the loss of cultural heritage sites as a result of climate change, urban development, natural disasters, and armed conflict. CyArk uses LiDAR or laser scanning.

Digital Reconstruction of a Medieval City	streets, palaces, churches, and offices in Florence during this time period. This platform allows people to read the interpretations of these places written by people in the 17th, 18th, and 19th centuries.	e+as+it+was&ie=UTF-8&oe=UTF-8 (Accessed on 20. 05. 2025) Embedded viewer

Tab. 4 Overview of Online Platforms for Sharing and Presenting 3D Cultural Heritage Models (adapted directly from Cieslik 2020) This table is based on Emma Cieslik's *3D Digitization in Cultural Heritage Institutions: A Guidebook,* 2020, Dr. Samuel D. Harris National Museum of Dentistry. Appendix 2, pages 74–75. It reflects the state of 3D platforms as of 2020. Further above in this thesis (see Tab. 2) an updated list of platforms has been compiled to reflect developments over the past five years. The present table builds on Cieslik's work and extends it with current data up to 2025, with a particular focus on open-access repositories, sustainable formats, and institutional infrastructure.

NAME OF 3D PLATFORM	DESCRIPTION OF 3D PLATFORM
Thingiverse	This platform is dedicated to sharing user-created digital design files. All models on this website are free to download. This platform is useful for 3D printing (Johnson et al. 2017).
Sketchfab	This platform supports the upload, publication, and visualization of 3D models on the web and supports the inclusion of 3D content in standard web pages and social media. This is the most commonly used viewer for cultural heritage content.
MyMiniFactory	This platform houses 3D models that can be purchased. This website also houses the models for the Scan the World project, asking all uploaders if they are Scan the World affiliated.
3D Heritage Online Presenter (3DHOP)	This platform is more flexible than Sketchfab in supporting more presentation and interaction modes. 3DHOP is based on the SpiderGL library, implementing plug-free free 3D rendering on web browsers.
p3d.in	This platform allows for models to live on the cloud, meaning that it runs on all modern web browsers without requiring a plug-in to download. This platform allows 3D models to be taken on tablets or mobile devices but only accepts OBJ uploads.
Universal Viewer	This is an open source platform to allow sharing 3D content. The benefit to this website is that it is zoomable, embeddable, extensible (supporting 3D), and securable, allowing content to be password protected.
Google Poly	This platform allows for the upload of 3D objects on the web. This platform also houses virtual reality products, Tilt Brush and Blocks. Many of the objects have low-polygon style, which fits with Google's Daydream platform which allows it to run more efficiently if the object is less complex.

Author Biography

Šárka Vyhnánková is a graduate student in Cultural Heritage Conservation and Management at the University of Applied Arts Vienna, and in the conservation of polychrome sculpture at the Faculty of Restoration, University of Pardubice. She specialises in the conservation of sculptural works and architectural surfaces, with a strong research focus on the ethical and material implications of 3D printing in restoration practice. Her practical experience includes work on stone, plaster, stucco, and painted architectural surfaces across Central Europe. She currently serves as the castle manager of Lešná Chateau in Czech Republic, which is a part of the Wallachian Regional Museum. This thesis draws upon her dual academic training and fieldwork experience, aiming to bridge emerging technologies with professional conservation ethics.