# A reproducible workflow for the creation of digital twins in the cultural heritage domain

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## Abstract

This article explores how to create reproducible workflows for the 3D acquisition and digitisation of cultural heritage objects to ensure sustainability and reusability across various institutions. By addressing two main research questions, the paper proposes a workflow that involves the systematic acquisition, processing, and digitisation of cultural heritage artefacts. In particular, the workflow focuses on developing digital twins for cultural heritage settings and exhibitions and proposes baseline standards for both technical and interpretative aspects of digitisation. The workflow has been derived and tested on the pilot case of the temporary exhibition *The Other Renaissance: Ulisse Aldrovandi and the Wonders of the World* in the context of the CHANGES project. We reflect on the software and hardware equipment, the procedures and techniques to use, and the formats to adopt to comply with openness, accessibility, transparency, reproducibility, reusability and sustainability of the research workflow by backing on previous works on fostering reproducibility in research and improving the interoperability of 3D data across different systems. It highlights the necessity for transparent documentation of every step of the process, focusing on accountability and practices in the context of cultural heritage research. Finally, the article suggests improvements to enhance the sustainability of these kinds of workflows and discusses future directions for digitisation efforts and sharing research practices.

**Keywords:** Digital Twin, Reproducibility, 3D models, Digitisation

# 1. Introduction

Reproducibility is a term longly discussed in science and spaces from the medical domain, as introduced by Niven et al. (2018), to the humanities, e.g. (Peels and Bouter 2018). Several scientists around the globe now agree that we are currently facing a reproducibility crisis in research (Peng 2015; Baker 2016; Hutson 2018). However, how reproducibility is interpreted and how it affects research and the related crisis depends on the kind of research and, thus, the scholarly domain we are considering. Indeed,

> “There seems to be an agreement on the fact that research can be reproducible in varying degrees, from an "ideal" computational reproducibility all the way to fields where multiple interpretations of a certain phenomenon coexist”. (Barzaghi et al. 2024a).

Considerations about reproducibility also affect those areas of humanities studies that deal with the adoption of computational methods for enhancing and revealing specific intrinsic values of humanities research, such as the valorisation and preservation of cultural heritage. European and international institutions, such as the EU and UNESCO, have recently supported several activities through grants to foster increasing digitisation efforts to preserve and make cultural heritage more accessible to all audiences, to offer innovative visitor experiences, and to let the audience access exhibitions remotely and see also the artefacts that are not currently displayed in a museum.

However, even if technological tools mediate the acquisition and digitisation of cultural heritage artefacts, the researchers involved in these activities act on subjective interpretations, bringing in different viewpoints, theoretical backgrounds and previous assessments that affect how the study is conducted and how the results are interpreted (Barzaghi et al. 2024a). These activities, situated within the humanities domain, often involve objects "with *meaning* and *value*, objects such as paintings, texts, statues, and buildings—in opposition to, say, such objects as atoms and viruses that are studied in the natural sciences" (Peels 2019, 2). Thus, working on the reproducibility of the CH acquisition and digitisation activities may vary from what is seen in other scholarly domains. In addition, other intrinsic factors – such as the practices and instrumentations of a particular research group and the cultural policies of a country – may not depend directly on the type of research conducted and affect the reproducibility of such activities.

Precise documentation of the study design, data collection, and analysis techniques adopted for the acquisition and digitisation of cultural heritage artefacts – i.e. the definition of a detailed workflow for the research to be conducted – is crucial to highlight all influencing factors and, thus, to provide the pillars to foster reproducible acquisition and digitisation activities of cultural heritage objects. The present article aims to present the experimentation we have run in the past years around this topic to answer the following two research questions (RQs):

1. Which material, methods, and tools can be used to implement a reproducible workflow for acquiring and digitising 3D cultural heritage artefacts?
2. How can we improve the current practices and tool adoptions to enhance the reusability and sustainability of the workflow?

In the work we have done in the context of Project CHANGES - Spoke 4 (https://www.fondazionechanges.org/spoke-4/), we have faced reproducibility issues in the definition and implementation of specific sub-projects whose main activities focus on the acquisition and digitisation of cultural heritage objects and the creation of digital twins of museums' exhibitions, aiming at improving the valorisation and preservation of cultural heritage. In this context, we have considered a set of case studies which involve heterogeneous cultural institutions, which include natural history and scientific museums, widespread art galleries, site museums with (in)tangible heritage and landscapes, historical palaces, demo-ethnic anthropological museums, and museums with extensive collections and high-tech approaches.

To come up with acquisition and digitisation guidelines that can be used by the different partners (including external companies) involved in all case studies considered in the project, we have worked on a pilot study that could serve as a common experimental ground and a baseline to define a precise and reproducible workflow for the acquisition and digitisation of 3D cultural heritage assets: the temporary exhibition entitled *The Other Renaissance: Ulisse Aldrovandi and the Wonders of the World* (https://site.unibo.it/aldrovandi500/en/mostra-l-altro-rinascimento). As described in prior research on this topic (Balzani et al. 2024), the goal of this activity was "to obtain a digital version of the experience at the exhibition, starting from its digital twin, connected to the digital asset of the different items (3D and multimedia) of the collections, organised and accessible online by users, using various devices (from home computers, smartphones, to tablets and VR headsets)".

As a direct consequence of the previous work mentioned above, this article introduces the reproducible workflow we have devised for structuring acquisition and digitisation campaigns across all nine case studies involved in the project. Thus, it complements the guidelines previously released for FAIR (Findable, Accessible, Interoperable, Reusable) management of 3D data in cultural heritage (Barzaghi et al. 2024b) by adding in-depth information about all the phases of the acquisition and digitisation workflow developed and reused as well as all the phases necessary to create a digital twin of cultural heritage events such as exhibitions. In particular, we defined step-by-step operational instructions with a strong focus on research interoperability, transparency, openness, and accountability, highlighting the need for documenting every step of the 3D model creation process to ensure reproducibility and clarity, particularly since reality-based models can be influenced by human or software interpretation.

The rest of the article is organised as follows. In Section 2, we introduce the most relevant related works about reproducible workflows for 3D acquisition and digitisation of cultural heritage, 3D interoperable formats for storing and exchanging 3D models, and techniques for creating digital twins. Section 3 answers RQ1 since we present there the main steps defining our reproducible workflow for acquiring and digitising objects and creating digital twins of events in the cultural heritage domain. RQ2, instead, is addressed in Section 4, where we discuss possible further improvement of the workflow to foster better reusability, interoperability, transparency, openness, and accountability of the process. Finally, in Section 5, we conclude by sketching out some future works.

# 2. Related Works

## 2.1. Reproducible Workflows for 3D Digitisation of Cultural Heritage

The 3D digitisation of cultural heritage assets has become a common practice, aiding the understanding, preservation, and promotion of culturally and historically significant sites and artefacts. As museums seek to innovate traditional exhibitions and enhance the appeal of their permanent and temporary collections, the demand for 3D digitisation of artefacts is steadily increasing (Raimo et al. 2021; Farella et al. 2022a). However, creating 3D digital replicas, or *digital twins* of museum assets, is often challenging and labour-intensive. The process for achieving this result is widely adopted in the literature (Raham et al. 2019; Raham and Champion 2019; Demetrescu et al. 2020; Apollonio et al. 2021; Benítez et al. 2022; Peinado-Santana et al. 2021; Sebar et al. 2021; Farella et al. 2022a; Farella et al. 2022b; Bolognesi and Manfredi 2024) and generally includes a data acquisition phase, a data processing phase, the mesh and texture generation, and finally, optimisation for web visualisation.

A literature review reveals that in many digitisation processes within the GLAM sector the same challenges arise (Farella et al. 2022a). First, virtualisation projects often encompass extensive collections (Guidi et al. 2013; Malik and Guidi 2018) and the integration of objects with their context. Time constraints introduce further issues, especially for temporary exhibitions or restricted monuments typically closed to the public for preservation reasons. An interest in prototyping exhibitions emerges as a way to improve the set-up of physical exhibitions (Pescarin et al. 2018). For example, Benítez et al. (2022) describe the task of digitising the Torre de la Cautiva, where the team had only a ten-hour window to complete the data collection. Furthermore, environmental factors such as inflexible lighting conditions, limited space, and the presence of visitors can impact the acquisition phase (Malik and Guidi 2018; Benítez et al. 2022; Vukovic et al. 2022). Adding to these intricacies, artefacts can vary significantly in shape, size, and material, requiring highly adaptable digitisation equipment to manage data acquisition across diverse conditions. In addition to selecting methodologies that optimise acquisition times, adequate time must be planned for processing and delivering 3D results, especially in large-scale digitisation projects. Finally, a significant challenge remains in ensuring the publication and accessibility of 3D model derivatives for reuse, including effective management of all the generated data during the process.

The documentation and accessibility of research outcomes and methodologies are essential for ensuring the reproducibility of workflows in any field. Concurrently, it is equally crucial to define an efficient methodology that meets certain basic requirements (Farella et al. 2022b) in terms of data quality, including a) an accurate, comprehensive, and precise reconstruction of the object's shape and geometry, minimising occlusions and preventing any loss of detail; b) high-resolution, realistic textures for optimised geometries, suitable for virtual inspection in web-based and/or augmented/virtual reality (AR/VR) applications; c) efficient acquisition and processing times per object to support large-scale digitisation efforts.

Additionally, the literature emphasises a growing need within the GLAM sector to develop accessible pipelines that can be replicated by less experienced staff and within limited budgets, providing a digitisation process more sustainable and scalable (Rahaman et al. 2019; Rahaman and Champion 2019).

Concerning the acquisition phase, the cultural heritage digitisation pipelines reveal that scanning technologies and photogrammetry are the most common acquisition methodologies (Apollonio et al. 2021). Photogrammetry, which offers advantages in terms of lower costs, adaptability, and reduced skill requirements, can achieve the same level of geometric accuracy as scanning when supported by metrology kits (Milosz et al. 2020; Sebar et al. 2021). This can be done, for instance, by placing markers that can be identified by the chosen processing software, enhancing accuracy in the capture process. In general, the most suitable acquisition technique is influenced by various constraints, including the object's surface type, size, location, geometric complexity, and the available space for acquisition. Scanners, for instance, have strict requirements regarding the acquisition distance range, whereas photogrammetry is more flexible and adaptable. Structured-light projection scanners, although costly, enable the rapid and accurate capture of large volumes of data in a very short time, proving advantageous when time constraints are tight. To optimise photogrammetry acquisition times while maintaining data accuracy, Menna et al. (2017) and Sebar et al. (2021) suggest automated techniques, such as rotating platforms, for digitising small to medium-sized objects, supported by open platform software to lights and shutter release's control. In this context, using a coded target grid significantly improves camera orientation and model scaling (Sapirstein 2018; Luhmann et al. 2023). To obtain a dense and geometrically reliable network (Luhmann et al. 2023), it is essential to rotate the platform in at least 30° angular intervals, ensuring overlap between adjacent shots (Lo Brutto and Spera, 2011; Menna et al. 2017) and preferably to replicate the rotation at least at two different elevations, thereby simulating a shooting geometry with multiple intersections. The use of acquisition schemas can further speed up the process by allowing for uniform and well-diffused illumination (Webb et al. 2020). Another key aspect is to adjust sensor settings to achieve adequate image quality and sharpness, aligning with the desired resolution for the intended 3D model. To obtain accurate colour data and exposure settings, colour checkers are generally used, such as the popular X-Rite ColorChecker Classic, which features 24 standardised patches with known reflectance values (Apollonio et al. 2021).

For structured-light scanner acquisition and processing, open-source software options like Open Scan (https://encr.pw/openscaneu) and 3DUNDERWORLD-SLS (https://3dunderworld.org/) are available. However, compared to proprietary systems, these options generally provide lower levels of detail and require technical adjustments that demand specialised skills (Gu et al. 2016).

In photogrammetry, standard workflows for data processing predominantly rely on proprietary Structure from Motion (SfM) software (Jones and Church 2020), with Metashape (https://www.agisoft.com/) being the most commonly used in academic settings (Vukovic et al. 2022; Chapinal-Heras et al. 2023). While proprietary software at date offers higher data accuracy and functions, open-source alternatives like Regard3D (https://www.regard3d.org/) and Meshroom (https://alicevision.org/) are gaining popularity (Rahaman and Champion 2019). Additionally, Reality Capture (https://www.capturingreality.com/), known for its processing speed, has recently provided a free version for students, educators, hobbyists and companies with annual revenues under $1 million USD, expanding the range of accessible SfM processing options.

In the reviewed studies (Medina et al. 2020; Chai and Li 2022), mesh retopology is mainly done using tools that facilitate automatic procedures such as Instant Meshes (https://github.com/wjakob/instant-meshes) (Jakob et al. 2015). Modelling and optimisation are often done together, with optimisation being crucial for publishing 3D models online. This typically involves low-poly geometries with high-quality PBR textures, depending on the project's goals. While high-poly models are used for research and documentation, optimised models are preferred for museum displays and AR/VR applications for dissemination and valorisation purposes (Peinado Santana et al. 2021). In this context, Apollonio et al. (2021) propose creating two versions of a model: a *Master Model* and a *Derived Model*, with the latter undergoing remeshing and optimisation for web-based visualisation.

The accessibility of 3D models for data reuse remains challenging. Institutional repositories often limit upload formats, while commercial repositories may lack reliable data provenance and integrity (Rahaman et al. 2019). Commonly used platforms in museum contexts include Sketchfab (https://sketchfab.com/), used by institutions like the British Museum and the Hellenic Museum of Melbourne, as well as the open Smithsonian's Voyager platform (https://smithsonian.github.io/dpo-voyager/), which hosts public 3D collections from multiple museums.

## 2.2. Overview of 3D formats usage in the international context

Despite the acknowledged importance of 3D in the digitisation of cultural heritage, at present, there are still no consolidated standards allowing for an effective design, monitoring, and reporting of the process, as highlighted by a recent survey promoted by the European Commission (2022) on parameters, formats, standards, benchmarks, methodologies and guidelines. This survey confirms the persistence of shortcomings that numerous previous studies had already pointed out, including specific aspects such as the absence of suitable repositories (Champion et al. 2020) or the lack of scientific rigour (Statham 2019) in the 3D assets published in the light of the recommendations contained in the London Charter (2009) and the Seville Principles (Bendicho et al. 2013). This lack of standardisation extends even to the formats themselves (Hernández-Muñoz 2023), where identification varies due to contingent boundary conditions, such as the prior expertise of the working group or the technological constraints imposed by the chosen method of publishing 3D assets, rather than, as it should be, to a prior and systematic evaluation of existing formats according to the specificities of cultural heritage objects and what follows.

Although the present article does not specifically focus on the systematic comparative analysis of existing formats, the definition of the workflow presented here nevertheless required a prior evaluation of existing formats to identify those that could be consistent with the general approach adopted and technically efficient throughout the entire processing flow, from raw data to publication.

The second crucial factor influencing the selection of a 3D format is its interoperability (Moore et al. 2022), which can be assessed at a technical level by the degree of compatibility with various software, and at a methodological one by determining whether it is proprietary or neutral. With respect to the latter, to facilitate the collaboration between different institutions and scholars involved in the field and the long-term preservation of 3D data, the use of open and program-neutral file formats is recommended (Moore et al. 2022). Nonetheless, this general indication may pose challenges, as programme-neutral formats typically result in the loss of metadata when converted from proprietary formats. On a practical level, however, this issue has relatively minor impact within the context of the presented workflow because the injection of metadata occurs during the final stages using a specific approach and ontology.

To ascertain which formats are used in real cases, an effective starting point is the studies by Champion et al. (2020) and Rahaman et al. (2019), where the authors identified and reported on the main formats used in publicly accessible repositories, both commercial and institutional, for the publication of 3D assets. In the plethora of formats identified, groupings can indeed be established based on both the field of use of choice and current dissemination. The latter makes it possible to identify formats that have been superseded by other formats like X3D or, lastly, are currently either used for restricted areas such as DXF and PLY or that only survive to maintain compatibility with old assets such as 3DS, LWO, IV, and WRL. There are also formats linked to specific software, such as BLEND with Blender (https://www.blender.org/), and others used for particular purposes such as STL (3D printing) and IGES (CAD).

The remainder can be categorised according to their preferred field of use, which is reflected in their adoptability for different stages of the workflow. For the sake of brevity, in the following list a systematic analysis of each format is not reported and the comparison has been performed at a qualitative synthetic level by compulsing the technical specifications of each format, when available.
Concerning raw data, in scenarios where Point Cloud data may be required, the PLY, LAS, and E57 formats have been identified as the most suitable and compatible options. No further assessment has been made since all three formats support additional data besides X,Y,Z coordinates and R, G, B values for each vertex of the Point Cloud, even if implemented with some specificity. Secondly, refining the raw data requires the adoption of specific features that can ease the task i.e. polygon/smoothing groups, layers, groups, weights, vertex maps and others across the whole process. A suitable format would support these features so that it would be possible to reprocess the data starting from any major phase taking advantage of all such features. Compatible formats, such as FBX, OBJ, USD, DAE, and ABC, are the most suitable options in line with these requirements. ABC is mainly used in the film industry whenever very complex scenes and VFX are implied. Both DAE and USD would fit, but DAE presents issues concerning compatibility and coherence amongst different software. In contrast, USD is emerging as a highly promising format and is experiencing increasingly widespread adoption, but it is less commonly seen in smaller-scale repositories and pipelines primarily due to factors like a lack of familiarity and training. Additionally, gaps in available conversion plugins and tools can hinder seamless integration into existing workflows. Alternatively, a more conservative approach not adopting it in the current iteration of the workflow, so that WIP assets have been stored just either in FBX or OBJ format.

OBJ instead is a geometry definition file format written in ASCII. It was first developed by Wavefront Technologies for its Advanced Visualiser animation package. It is a very simple data format representing 3D geometry alone - namely, the position of each vertex, the UV position of each texture coordinate vertex, vertex normals, and the faces that make each polygon defined as a list of vertices and texture vertices, while material definitions are supported via dedicated separate (MTL). Such simplicity implies that more complex features are generally not supported. OBJ, on the other hand, is very lightweight, making it a common choice for publishing 3D assets and, consequently, cemented its status as a common choice for 3D modelling and animation, even if it doesn't support complex features like animations or shaders. In fact, it is readable by almost any 3D application and directly uploadable on online repositories and Web3D viewers.

FBX was initially developed by a private company, Kaydara, that later became part of Autodesk. Introduced in 2001, FBX was designed as a platform-independent 3D data interchange format to facilitate higher-fidelity data transfer between various graphics software platforms. It offers both binary and ASCII formats and supports complex 3D geometry (mesh geometry, curves, surfaces, and volumes), advanced animations (skeletal rigging, bone-based animation, and keyframe animation), and scene data (materials, texture, and shader information, along with lights, cameras, and scene settings). FBX is compatible with the most part of 3D authoring software, hence it may be regarded as a standard de facto, even if it cannot be considered an open format like OBJ because although Autodesk offers an SDK to interact with it, the format itself is still protected by Autodesk's intellectual property rights. The SDK allows developers to work with FBX files, but it comes with limitations, such as the need to comply with Autodesk's licensing terms. Nonetheless, its wide adoption and the efficient data compression that leads to smaller overall file size despite the support of all the main features required by 3D pipelines make it a reliable alternative choice when dealing with WIP complex 3D assets that make use of features that are not supported by OBJ.

Finally, the delivery format must be optimal for Web3D applications, both in terms of supported features and of format efficiency for real-time interaction and presentation. The latter is determined mainly by overall compactness in terms of size (network transmission) and memory footprint (textures, etc.) to target different devices with different limitations. It has to be noticed that many other aforementioned formats can be successfully used to upload 3D assets to online viewers and repositories, but none of them is specifically built for this purpose and hence accomplish the requirements of efficacy only to a partial degree. At present time, being X3D an increasingly less used format, glTF is effectively the only dedicated format for Web3D implementation. Additionally, glTF positively accomplishes the requirements of an ideal standard format for DCH, as European Commission (2022) has proposed: it can be used without conversion by a vast number of software applications, is interoperable and, lastly, is upgradable while maintaining backward compatibility by design.

More specifically, glTF (https://www.khronos.org/Gltf) is an open, royalty-free specification for the efficient transmission of 3D scenes and models by engines and applications (Robinete et al. 2018; Lentz et al. 2021). The format, developed by Khronos (https://www.khronos.org/), is designed for compactness and efficiency within real-time processing and rendering realms. glTF 2.0 is designed to be vendor-neutral and runtime-neutral. It can be employed by a wide range of native and Web3D applications, regardless of the underlying 3D graphics platforms and APIs.

The format has evolved beyond its origins as a standalone 3D format: it is nowadays widely adopted as an international ISO standard (https://www.iso.org/standard/83990.html), becoming the centrepiece of several rapidly growing ecosystems of software tools, standards, and extensions. The glTF focus on efficiency is a design goal that differs from typical 3D "authoring" formats: the latter are typically more verbose, with higher processing costs to transport data that is no longer needed for the final, interactive application. glTF is complementary to authoring formats, providing a common, interoperable distillation target for publishing 3D resources to a broad audience of end users.

Regarding materials and simulation of physical properties - often crucial for interactive presentation of CH assets - Khronos glTF PBR defines a set of parameters used within the format to approximate real-world lighting interactions and surface properties. The glTF efficient delivery, in combination with PBR realism (Pharr et al. 2023), became a game-changer for the 3D industry, empowering artists and developers to deliver visually captivating 3D experiences. A wide range of physical properties are supported by the format, with accompanying material extensions, including: Base Color, Normal, Alpha Coverage, Ambient Occlusion (AO), Emissive, Metalness, Roughness, Anisotropy, Clearcoat, Dispersion, Index of Refraction (IoR), Iridescence, Sheen, Transmission, Volume and much more. The glTF open standard, with its interoperability and extensibility (as JSON format), represents a suitable solution for universal delivery, strongly aligned with FAIR principles.

## 2.3 Accessible digital twin creation with 360° immersive photos and 3DGS

Panoramic 360° photos are a powerful tool for creating digital twins that are lightweight, cost-effective, and easily accessible. Unlike traditional 3D scanning technologies, which require complex equipment and significant computational resources, 360° images allow for faithful capture and reproduction of cultural and natural environments with remarkable simplicity. Using 360° cameras or even smartphones, it is possible to produce immersive reproductions of spaces and exhibits without the need for expensive, advanced equipment.

These images can be viewed directly on web browsers, eliminating the need to install specialised software or use devices with high computing capacity. This accessibility makes them a sustainable and scalable solution for cultural heritage promotion, capable of reaching a global audience with minimal technological effort. In a context where sustainability and accessibility are increasingly central, 360° photos function as interoperable, flexible, and ready-to-use digital twins, ideal for museums, cultural institutions, and educational projects that aim to offer high-quality digital experiences with minimal economic and environmental impact.

Considering immersive photos as a "lightweight" form of digital twin makes it easier to provide access to objects and exhibition spaces, while also enhancing the user experience. Furthermore, this approach aligns with FAIR principles, making data findable and reusable through well-structured online repositories and promoting interoperability with other digital resources. Obviously, to fully adhere to these principles, some additional metadata structure is needed for management. Standard formats such as JPEG and PNG for images, along with JSON or XML for metadata, ensure seamless integration with other systems.

Finally, regarding interoperability, 360° JPEG photos can be converted into other formats, such as 3D glTF, when needed. Open-source tools like Blender make this conversion possible. The process typically involves importing the JPEG as a background or environment texture in Blender, building a simple 3D structure to align with the image, and then exporting the model in glTF format. This method adds flexibility for various applications, making 360° immersive photos an effective tool for documentation, accessibility, and enhancing the experience of cultural heritage.

Alongside these aspects of simplification of representations in the cultural heritage field, we can also add new techniques for the creation of accessible and fairly accurate digital twins, which is undoubtedly one of the main challenges. In this context, we can note the emergence of innovative methods such as "Gaussian Splatting" (Kerbl et al. 2023) that is revolutionising the field by offering a more streamlined and accessible solution. With the ability to generate realistic 3D models using even mobile devices such as smartphones without the need for expensive professional equipment, Gaussian Splatting allows the creation of lightweight and rapidly produced digital twins, viewable via simple Web browsers. This solution can be quite accessible, even if at the moment there are some limitations on the visualisation parameters of the Gaussians and applicability with not too large data sets, but it still has good prospects for improvement on these aspects. Therefore, compared to traditional methods, this technique democratises access to 3D modelling, making it accessible to museums and cultural institutions of all sizes and opening up new opportunities for digital engagement.

## 2.4 Metadata for traditional and digital CH objects

In the digitisation of cultural heritage, metadata plays a pivotal role and requires specific adroitness. In the first place, transposing museographic information in a digital environment implies a rigorous transferring of the existent metadata concerning the digitised object, allowing for an enhancement of their informative value, for example through semantic web technologies. In addition to that, it must be noted that the digitisation process itself produces new metadata concerning the creation of the digital objects, which are at the same time directly derived from the original ones and also entities of their own right, with an independent set of metadata concerning creation and evolution over time. For this reason, every step of the 3D model creation process should be documented to ensure reproducibility and clarity, also considering that reality-based models can be influenced by human or software interpretation (Moore et al. 2022; Barzaghi et al. 2024a).

Having a well-defined and rigorous pipeline for the metadata management factually increases the informative enhancement potential, allowing, for example, for data visualisation, improved exploration, tracking of provenance and changes over time, with the possibility of exploiting research products whose effectiveness has already been tested in previous case studies. Despite not many workflows for the management of metadata concerning 3D cultural heritage objects are openly available, we list below some relevant studies published on the topic and their proposed approaches.

Some early works explicitly depicting pipelines for the aforementioned purposes date back to more than a decade ago. Starting in 2010, the CARARE project allowed for the definition of a metadata schema for GLAM 3D digitised objects, required for their inclusion in the Europeana platform (D'Andrea and Fernie 2013). As a continuation of the research, the 3D-ICONS project allowed enriching Europeana with a considerable amount of 3D models of archaeological and artistic items, shedding light on the necessity of defining a structured workflow for univocally identifying the items, making the them publishable and harvestable in the platform through their descriptive metadata, and tracking the progression of the digitisation process via technical ones (Guidi et al. 2013).

Around the same years, proposals for the semantic exploitation of metadata concerning 3D contents emerged, such as the definition of a RDF-compliant methodology for harvesting Extensible 3D (X3D) web content by the use of the Gleaning Resource Descriptions from Dialects of Languages (GRDDL), allowing semantic descriptions of real-world objects and their digital 3D reproductions referenced by URIs (Flotyński 2013). The exploitation of metadata to enhance 3D digital items search is also addressed in a study (Kolosova and Hermon 2013) focusing on the real-time items visualisation and the user experience in the X3DOM framework, thanks to metadata files associated to each object, allowing for enhanced navigation experience through contents. The research concerning the AR/VR sector also contributes to the advancement in formalising procedures for a proper management of metadata concerning 3D digitised CH objects. An example is the 5W1H-based metadata schema for context-aware AR application, which links physical points of interest (PoI) to AR contents through AR anchors and semantically defines the context through the five w-questions and the specification of the interaction modality (Kim et al. 2015).

Nowadays, new interesting formalisations of metadata management pipelines are proposed, with the aim of exploiting information about 3D digital items as linked data. A recent study concerning ontologies and metadata schemas for the 3D capturing process of heritage objects stressed the nature of the digitisation as a metadata productive activity in each of its substeps, and highlighted the necessity of tools and guidelines for properly registering the informative content. The researchers produced a metadata schema specifically based on the 3D scanners used in the case studies (concerning a Roman burial monuments in Trier, Assyrian cuneiform tablets, and the preservation of antique wood samples), but they also openly published the obtained datasets on Zenodo (https://about.zenodo.org/), with examples for an accessible reproduction of the proposed workflow execution. In addition to that, they extended the free and open-source GigaMesh Software Framework (https://gigamesh.eu/) to provide metadata about the steps concerning 3D processing (Homburg et al. 2021). Newest studies make more and more evident the necessity of reusing existing standards instead of increasing the number of purpose-specific ones produced ad-hoc for a case study. Concerning this, a 2023 publication (Amato et al. 2023) depicts the procedure adopted for the metadata management in two study pilots, one about Samnites settlements and the other on the Roman Appia road, mentioning the importance of adopting Application Profiles drawing components from existing namespace schemas and optimise their combinations for local applications.

Focusing on reproducibility, metadata related to objects, processes, and provenance data are pivotal aspects in the definition of workflows for the cultural heritage domain (Barzaghi et al. 2024b). In this regard, a notable example is the tailored set of FAIR principles introduced in 2018 specifically for Heritage Libraries, Archives, and Museum Collections, which aims to emphasise the role of metadata (Koster and Woutersen-Windhouwer 2018). This work defines three distinct "levels" of metadata: the object level (e.g., artefacts, datasets), the object metadata level (e.g., title, creator), and the metadata records level (e.g., the comprehensive metadata elements about the object). The process/workflow data plays a key role in generating the metadata that accompanies the artefacts representing the digital cultural heritage objects created during the digitisation process.

The definition of metadata should account for both their model and representation schema, as these are crucial for data exchange and interoperability. In this regard, efforts have been made to provide guidelines that enhance data exchange across various levels – technological, semantic, organisational, legal, and syntactic. This includes the development of a crosswalk for data models, vocabularies, and aggregator guidelines (EOSC Executive Board 2021). Crosswalk practices for interoperability improvement include making metadata available as linked open data, reshaping it into a Resource Description Framework (RDF) format serialisation. A powerful tool for structured data conversion into semantic triples is the RDF Mapping Language (RML) (Dimou et al. 2014). Assuming the non-triviality of the mapping task, RML provides a wide and detailed documentation, and allows the user to potentially avoid or significantly limit the interaction with the code to the definition of RDF mapping files in which they can describe the rules to convert a JSON or a CSV file into a RDF serialisation, adopting a data model of their choice. A more human-friendly option is also provided, based on the use of an easy YAML file, whose low level of abstraction makes the procedure more accessible to less expert users (Heyvaert et al. 2018). In case the built-in functions do not fulfil the user requirements for converting their input dataset, the JAVA codebase can be extended. To improve the factual reuse of this mapping approach, a tool named Morph-KGC (Arenas-Guerrero et al. 2024a) was developed in Python, broadening the potential use base capable of extending the code with new user-defined functions (Arenas-Guerrero et al. 2024b).

For the long-term preservation of the resulting collections of information and maintaining their trustworthiness, supporting the tracking of both Object Provenance Information (OPI) and Metadata Record Provenance Information (MRPI) is a pivotal aspect. It is essential in this regard to capture changes in data and metadata over time, as digital representations of artefacts often evolve, either due to new findings or advancements in digitisation technologies. One possible practical approach to storing provenance and tracking data changes is through the OpenCitations Data Model (OCDM) (Daquino et al. 2024). OCDM provides a framework that enables comprehensive documentation of the entire lifecycle of digital artefacts using Semantic Web technologies. It captures snapshots each time an entity is created, modified, merged, or deleted, saving these within a provenance-named graph. Each snapshot includes information on validity dates, responsible agents, primary sources, and a link to the prior snapshot, thereby ensuring a transparent and traceable record of data changes.

# 3. Acquisition and digitisation workflow

## 3.1. Managing objects and processes metadata

The metadata management process in a digitisation workflow that aims to be reproducible involves a series of prerequisites. First, objects (both physical and digital) must hold a unique global persistent identifier. Second, the objects must be described with metadata, including the specification of their global persistent identifiers. Third, metadata record themselves must also have their own unique global persistent identifiers. In addition, metadata are produced and managed at various levels, and as such they include not only those related to the exhibited objects, but also those resulting from the digitisation process itself.
A wide array of technologies and methods are employed to develop and gather 3D data. In our case study, we chose to retain three distinct versions of each 3D model in addition to the raw material (RAW) generated during the acquisition phase:

- Processed Raw Model (RAWp): This is the preliminary output from the photogrammetry or scanner software, produced after data processing but without any interpolation or geometry corrections.
- Digital Cultural Heritage Object (DCHO): This version includes interpolation, gap filling and resolution of geometric issues, creating a refined model.
- Optimised Digital Cultural Heritage Object (DCHOo): This version is optimised for seamless, real-time online interaction.

Metadata production and management in the digitisation process started off with data collection, which involved the creation of two tabular datasets, one for registering cataloguing information (bibliographic data) about the physical cultural heritage objects (CHOs), and another for collecting information created during the acquisition and digitisation activities (process data), as well as the metadata accompanying the DCHOs created during digitisation. The creation of the tables involved the definition of their structure, column names, expected cell data and controlled values for certain columns (with their values aligned to existing authority files as well). While the bibliographic data table was structured according to official sources (such as the exhibition catalogue and curators' notes), the process data table was based on the steps that are part of a digitisation process and the attributes deemed to be relevant for tracking the provenance of each step.

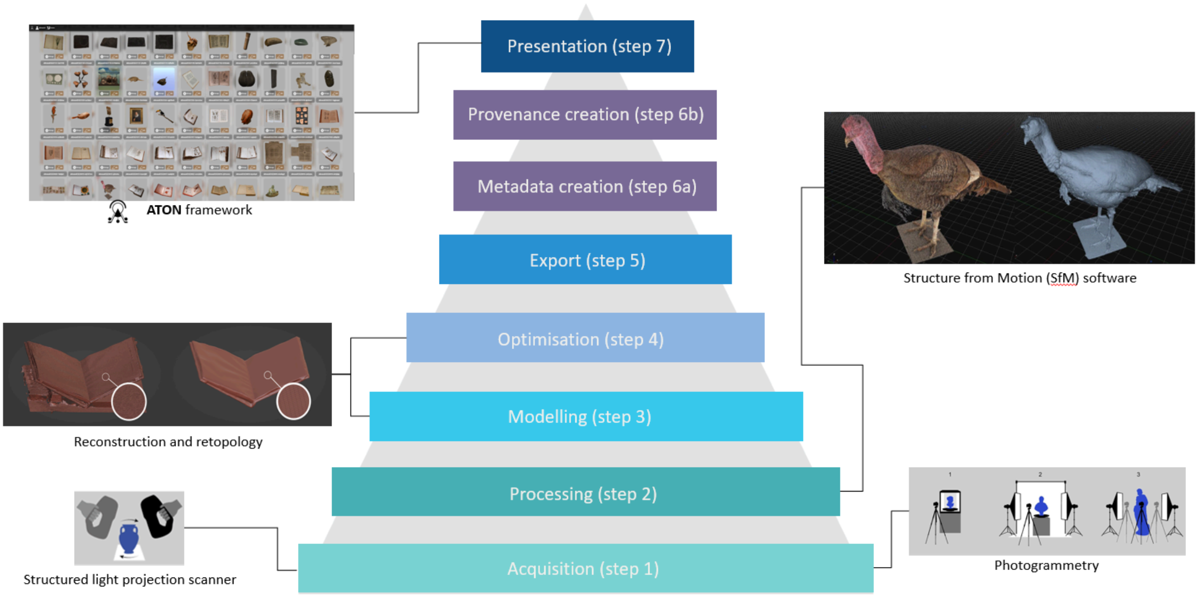


*Fig. 1: The acquisition and digitisation process.*

In particular, as summarised in Figure 1 and as explained in the next sections, the Acquisition phase (Section 3.2.1) aimed to capture CHOs and the RAW material needed to create the related DCHOs. After the acquisition, the generated raw data is then reused in the rest of the digitisation process through a sequence of activities, which may vary depending on the nature of the materials to be digitised and the intended use of the digital files. However, the common procedure tends to involve the following:

- a Processing phase (Section 3.2.2), in which the RAW data produced during the acquisition phase is used to produce a processed raw model (RAWp) using automatic algorithms (with the human operator setting the input parameters);
- a Modelling phase (Section 3.2.3), in which the human operator resolves any topological issues in the RAWp, making, when needed, subjective interpretative contributions, resulting in the creation of the DCHO;

- an Optimisation phase (Section 3.2.4), which simplifies the DCHO for specific use purposes, creating an optimised DCHO (DCHOo);
- an Export phase (Section 3.2.5), in which the RAWp, DCHO and DCHOo are converted into a specific format;
- a Metadata creation phase (Section 3.2.6), in which the metadata tables are exported in CSV format, and then converted into RDF N-Triples to create structured information on bibliographic and process data for CHO, RAW, RAWp, DCHO, and DCHOo;
- a Provenance creation phase (Section 3.2.7), in which provenance information is tracked and created for each metadata record;
- a Presentation phase (Section 3.2.8), in which the DCHOo is moved from a local device or storage location to a Web-based framework (e.g. ATON).

In this context, we are creating a specific and detailed document aimed at providing best practices tested within the current project to support companies involved in the digitisation of cultural heritage. Our guidelines are aligned with those established by the Italian Ministry of Culture (MiC) (https://digitallibrary.cultura.gov.it/linee-guida/), with certain aspects simplified, as our guidelines are intended for purposes of valorisation and dissemination rather than for documentation objectives, as in the case of the MiC.

Each of the phases described above results in the production of distinct objects and their corresponding metadata, which must be properly recorded and described. Based on the bibliographic and process data collected in the tables, along with the metadata used to describe them, a semantic data model was developed to represent both CHOs and the various versions of DCHOs, as well as the processes involved in digitising the former into the latter, to support the reproducibility of the entire digitisation workflow. To achieve this, existing standards were reused, including the CIDOC Conceptual Reference Model (CIDOC-CRM) (http://www.cidoc-crm.org/cidoc-crm/) (Doerr 2003), the Object-Oriented Library Reference Model (LRMoo) (http://iflastandards.info/ns/lrm/lrmoo/) (Riva et al. 2022), the CRM Digital extension (CRMdig) (http://www.cidoc-crm.org/extensions/crmdig/) (Doerr and Theodoridou 2011) and the Art & Architecture Thesaurus (AAT) (http://vocab.getty.edu/aat/) (Harpring 2010). In addition, the model's development and documentation followed the Simplified Agile Methodology for Ontology Development (Peroni 2017), which further contributes to the reproducibility and reusability of the overall process. The result was the creation of the *Cultural Heritage Acquisition and Digitisation - Application Profile* (CHAD-AP) (https://w3id.org/dharc/ontology/chad-ap) (Barzaghi et al. 2024c), an application profile encoded in OWL for describing CHOs, DCHOs, and the processes of acquisition and digitisation in the cultural heritage domain as structured, machine-actionable data.

As detailed in Section 3.2.6, once data collection is complete, the metadata tables were exported in CSV format, and then converted into RDF N-Triples to create structured information on bibliographic and process data for CHO, RAW, RAWp, DCHO, and DCHOo, using the CHAD-AP data model as the vocabulary for semantic representation and the custom extension of the Morph-KGC software for converting the data into a knowledge graph based on said model.

## 3.2. Assets acquisition and digitisation workflow

In this section, we describe the main activities of all the phases, introduced in Figure 1, that characterise the acquisition and digitisation process of the CHOs involved in the temporary exhibition. The 301 CHOs featured in the exhibition were primarily from the permanent collection of Palazzo Poggi, with a smaller selection on loan from various cultural institutions (Balzani et al. 2024). The CHOs presented a wide range of characteristics in both geometric shapes and surface properties, which added further challenges to the existing time and space constraints. The digitisation process included a variety of materials, such as paper-based items like manuscripts, printed books, and historical maps, as well as woodcuts, technical/scientific instruments, statues, specimens, and archaeological artefacts.

In Figure 2, we represent the 3D data taxonomy obtained and established as a research output by testing this specific digitisation process. The schema serves as a reliable methodological reference model for future projects.

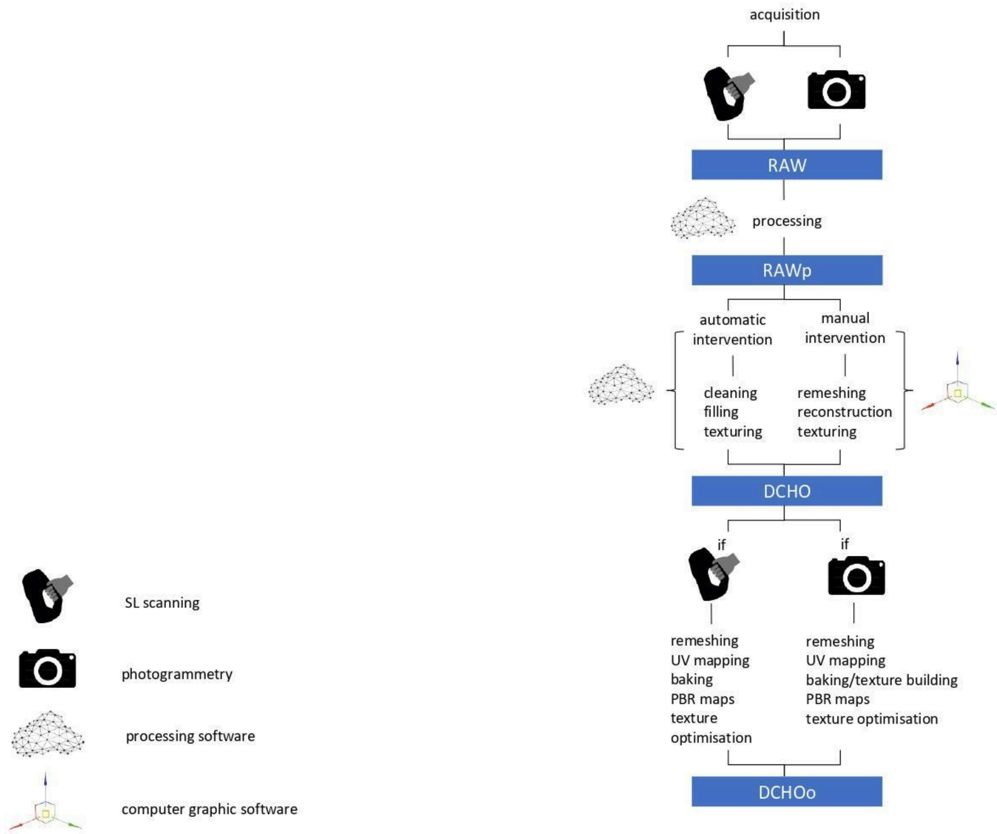


*Fig. 2: 3D data taxonomy established as research output.*

### 3.2.1. Step 1: Acquisition phase

The work began with a thorough analysis of the artefacts and the acquisition spaces. Managing such an extensive and diverse collection required the use of established techniques. Table 1 was created to represent the main types of objects and cases encountered during digitisation. The objects presented summarise the main problems and characteristics that influenced the choice of the acquisition methodology and the interventions in the following phases.

Consequently, the acquisition process employed reliable remote-sensing technologies frequently used in cultural heritage preservation and accessible to the various research groups involved, such as 3D structured-light scanning (SLS) and digital photogrammetry (Bitelli et al. 2007; Apollonio et al. 2021). Each CHO to be surveyed was initially examined and classified based on dimensions, geometry, surface irregularities, material properties, manoeuvrability, and accessibility.

Based on these characteristics, the most suitable methodologies, problem mitigation strategy, tools, and thresholds for geometry and image resolution were identified and established. For example, the use of structured-light projection scanners requires strict adherence to a specific acquisition distance range and necessitates that the operator be able to move around the CHO to maintain the correct distance. This was not always feasible when obstacles or limited space were present. In cases where space was restricted or CHOs could not be moved, we opted for photogrammetry, which is less constrained by acquisition distance than the structured-light projection technique (Ruiz et al. 2022).

Additionally, the limited time available for object acquisition, due to the temporary nature of the exhibition, made structured light scanning a valuable tool for capturing large volumes of data quickly. We used all available equipment to achieve our objectives and gather satisfactory data in the shortest time possible. Generally, we prioritised the use of structured-light scanning for movable, medium-to-small CHOs (such as coins, woodcut tablets, etc.) with intricate details, while photogrammetry was applied to both movable and immovable medium-to-large CHOs (e.g., specimens, manuscripts, scientific instruments, etc.). However, depending on the type of the CHO to be digitised, the teams could select from various scanner models suited to different CHO sizes.

| | Object scale | Operating conditions | Acquisition Technology, Equipment and Devices | RAW data | RAWp data | DCHO | DCHOo |
|---|---|---|---|---|---|---|---|
| **Rattle with Thevetia peruviana seeds**<br> | • Small scale object, complex geometry<br>• Bounding box diagonal: 11.34 cm | • **Surface complexity:** fragile object, without the possibility of being rotated, complex and articulated geometry<br>• **Acquisition scheme:** capture from one side only, Lightbox with turntable, fixed camera on a tripod | **Photogrammetry**<br>Panasonic DMC-LX100<br>CMOS 17.3 × 13mm<br>4112 × 3088px<br>4.19 µm<br>24–75 mm<br>GSD: 0.003 | • n. photos: 54<br>• n. target: 4 | **Processing:**<br>3df Zephyr<br>• Vertex: 212,315<br>• Polygons: 164,152<br>• Texel: 2,27 mm/pixel<br>• Texture 8k | • Solving non-manifold issues<br>• Authorial intervention: of the back of the seads and the joining threads<br>• Texture 8k | • Automatic retopology in Instant Meshes<br>• Vertex: 64.538<br>• Polygons: 65.025<br>• Texture 4k<br>• PBR maps: 2k-4k |
| **Adnotationes animalibus volume**<br> | • Medium scale object, simple geometry<br>• Bounding box diagonal: 46.43 cm | • **Surface complexity:** fragile object, without the possibility of being rotated, constant presence of museum staff needed<br>• **Acquisition scheme:** non-movable objects, 2–4 continuous led lights on stands and cameras on tripods (moved around the object) | **Photogrammetry**<br>Panasonic DMC-LX100<br>CMOS 17.3 × 13mm<br>4112 × 3088px<br>4.19 µm<br>24–75 mm<br>GSD: 0.003 | • n. photos: 38<br>• n. target: 8 | **Processing:**<br>3df Zephyr<br>• Vertex: 60.179<br>• Polygons: 119.983<br>• Texel :1,439 px/mm<br>• Texture 8k | • Solving non-manifold issues<br>• Authorial intervention: reconstruction of the back<br>• Texture 8k | • Automatic retopology in Instant Meshes<br>• Vertex: 31.927<br>• Polygons: 63.850<br>• Texture 4k<br>• PBR maps: 2k-4k |
| **Wooden Sawfish matrix**<br> | • Medium scale object, simple geometry<br>• Bounding box diagonal: 34.77 cm | • **Surface complexity:** movable object, good state of preservation | **Light Structured Scanner**<br>Artec Space Spider2a<br>3D point precision: 0.05 mm<br>3D resolution: 0.1 mm<br>Texture resolution: 1.3 MP<br>Acquisition surface: 90x70 mm, 180x140mm<br>Acquisition distance: 20-30 cm | • Fps: 6-7 | **Processing:**<br>Artec Studio 16<br>• Vertex: 1,614,083<br>• Polygons:3,228,162 | • Solving non-manifold issues<br>• Texture 16k-8k | • Automatic retopology in Instant Meshes<br>• Vertex: 6684<br>• Polygons: 12456<br>• Texture 4k<br>• PBR maps: 2k-4k |
| **Quetzal bird embalmed model**<br> | • Medium scale, non-Lambertian and unconventional materials<br>• Bounding box diagonal: 135.3 cm | • **Surface complexity:** object in non-removable glass case, complex and articulated geometry, inconsistent surfaces (feathers)<br>• **Acquisition scheme:** 2–4 continuous led lights on stands and cameras on tripods moved around the object | **Photogrammetry**<br>Canon EOS 6D<br>CMOS 36x24mm<br>5472x3648px<br>6.54 µm<br>50mm<br>GSD: 0.008 | • n. photos: 112<br>• n. target: 13 | **Processing:**<br>Metashape<br>• Vertex:244, 979<br>• Volygons:489,135<br>• Texel: 0.001px/mm<br>• Texture 8k | • Solving non-manifold issues<br>• Authorial intervention: modelling of the bird<br>• Alpha planes used for the feathers<br>• Texture 8k | • Automatic retopology in Instant Meshes<br>• Vertex:68,339<br>• Polygons: 84,271<br>• Texture 4k<br>• PBR maps: 2k-4k |
| **Narwhal horn**<br> | • Large scale, simple geometry and texture, cylindrical shape<br>• Bounding box diagonal: 281,51 cm | • **Surface complexity:** large, non-movable object, possibility to circle around the object | **Light Structured Scanner**<br>Artec Eva<br>3D point precision: 0.1mm<br>3D resolution: 0.2mm<br>Texture resolution: 1.3MP<br>Acquisition surface: 214x148mm 536x371mm<br>Acquisition distance: 40-100cm | • Fps:10 | **Processing:**<br>Artec Studio 16<br>• Vertex:1048049<br>• Polygons:2096094 | • Solving non-manifold issues<br>• Texture 16k-8k | • Automatic retopology in Instant Meshes<br>• Vertex: 69224<br>• Polygons:131004<br>• Texture 4k<br>• PBR maps: 2k-4k |

*Table.1: Master data from five CHOs, representing the variety of objects and methods used in the proposed workflow.*

This approach allowed for the adoption of optimal geometric resolutions and image quality standards during the acquisition phase, tailored to the specific features of each artefact, while allowing research groups to proceed simultaneously and efficiently with the digitisation process. Based on these premises, raw material of each CHO was captured using SLS or photogrammetry acquisition techniques.

SLS is an acquisition technique based on projecting calibrated blue or white light patterns onto the object's surface and obtaining its geometry in real time (Geng 2011). For the CHOs acquired with this technology proprietary software Artec Studio 15 Professional (https://www.artec3d.com/it/3d-software/artec-studio) and two structured light scanners from the company Artec with very high 3D point accuracy were used (Artec 3D 2023a; Artec 3D 2023b): Artec Space Scanner and Artec Eva, respectively, suitable for acquiring small-to-medium (from 1-5 cm to 100 cm) and medium-to-large objects (from 5-20 cm to more than 200 cm).

The first step was to set the *"Geometry + Texture*" scanner acquisition mode so that they could be captured simultaneously by the many dedicated cameras. Next, the most appropriate acquisition schemes were identified depending on the size of the CHOs and their manageability and accessibility (for SLS, immovable CHOs stored in non-opening display cases were not considered):

1. For small-to-medium-sized movable CHOs, manual or turntable movement of the CHO itself was chosen;
2. For small-to-medium and medium-to-large immovable CHOs, on the other hand, it opted to move the operator around the CHO and to use a ladder to reach even the highest and most difficult parts to acquire.

The CHOs were then captured following parameters like positioning the scanner at the appropriate distance from the CHOs and at the right angle (both before and during the captures), setting the FPS (Frames per Second) according to the characteristics of the CHOs, evaluating for "difficult to acquire" CHOs (shiny/reflective surfaces, with too narrow, dark geometries) to set different parameters for sensitivity and brightness of scans, also considering that higher sensitivity results in increased noise, keeping a valid area of overlap between one scan and the other, and making enough acquisitions to cover 100% of the visible/acquisitive surface of the CHO (McMillion 2022; Artec 3D 2020). In this case, the RAW consisted of a 3D point cloud stored in .SCAN format (Artec 3D scan format).

For CHOs acquired through digital photogrammetry, various configurations and equipment were used based on the CHO's size, material, and condition. The setup began with a controlled lighting environment, where diffuse light sources were arranged to minimise shadows and reflections, especially for non-Lambertian CHOs. Three configurations were employed to adapt to the size and mobility of the CHOs:

1. For small movable CHOs, a lightbox, a turning platform, and a fixed camera on a tripod were used to ensure controlled lighting and consistent angles.
2. For medium-sized movable CHOs, the setup included 2 to 4 continuous LED lights on stands, a photographic studio backdrop, a turning platform, and a fixed camera on a tripod.
3. For large or immovable CHOs, 2 to 4 continuous LED lights on stands were positioned around the CHO. At the same time, the camera, mounted on a tripod, was moved around it to capture all necessary angles.

The Ground Sample Distance (GSD) was calculated by determining the optimum sample resolution required to capture the sharpest detail on each sample. This calculation began with an assessment of the smallest feature that should be represented in the model. To achieve this, a ratio of 1:2 was applied, using Nyquist's theorem as a guide (Kraus 2011, 100), and consequently ensuring that the GSD was at least half the size of the smallest detail (i.e. if the minimum feature size required was 1 mm, the GSD was set to 0.5 mm) (Triglav Čekada et al. 2010, 7). This ratio allowed each pixel to represent a small enough portion of the surface to capture the desired level of detail and ensure that the texture generated from the images accurately represented the surface of the CHO. The GSD was determined by the distance of the camera to the CHO, the lens characteristics and the resolution of the camera sensor. By positioning the camera at an appropriate distance and choosing the correct lens and sensor resolution, the calculated GSD could be consistently achieved, allowing a balance between the level of detail required and the manageable data size. This systematic approach ensured that the average GSD across all images met the accuracy and resolution requirements of the project. However, as the CHOs are not flat and vary in shape, the GSD was approximate and often had to be adjusted. In cases where the CHO geometry made a precise 1:2 acquisition impossible, the GSD was occasionally set to a higher ratio, depending on the specific shape and surface complexity of the CHO in question.

For complete coverage of each CHO, we followed a 360° capture approach, moving around the CHO or using a turning table when possible at even intervals (around 15 degrees). This setup achieved an image overlap of 70-80%, providing sufficient data for accurate alignment and depth mapping during the processing phase. Camera settings were adjusted to capture sharp, high-quality images. Exposure, ISO, and aperture were modified to balance brightness and detail: a low ISO was used to reduce image noise, and a small aperture (f/11 to f/16) provided a greater depth of field, ensuring that all areas of the CHO remained in focus. Colour checkers were used to calibrate the white balance.

Finally, markers were strategically placed around the CHOs to serve as reference points during 3D reconstruction. These markers allowed for precise scaling and improved the alignment and positioning of images within the photogrammetric software, ensuring the resulting 3D model accurately reflected the artefact's geometry. To achieve this, different homemade marker configurations were used according to the acquisition configuration:

- Scale Bars: Rigid bars with coded markers placed at known distances, which provided reference points for scaling.
- Grids: Coded markers printed on a grid and evenly distributed, with known coordinates for each marker. The grid was placed beneath the CHO being surveyed or attached to the rotating platform.

Although a metrology kit, which could achieve sub-millimeter accuracy, was not used, the homemade marker setup provided sufficient accuracy (around 1 mm) to meet the project’s requirements.

During the acquisition phase, various cameras and lenses were selected based on the average GSD, CHO dimensions, and accessibility, with a preference for full-frame cameras equipped with standard lenses (35-50 mm). However, in some cases where accessibility posed challenges - such as with immovable CHOs or CHOs in fixed display cases - alternative solutions were required. These included using a panoramic camera (Insta360) or wide-angle lenses to capture areas that were otherwise difficult to reach.

### 3.2.2. Step 2: Processing phase

Once the raw materials have been captured, they are subsequently refined and processed using software tools.

As concerns scanned data, after acquisition from all necessary angles and obtaining a sufficient number of captures, the scans were refined with a view to the subsequent creation of the 3D model. As a first step, the original scans (RAW) were exported to have a copy in case of loss of the project or need to process a new 3D model. Before starting the generation of the RAWp, a review of the scans was performed to detect any acquisition errors. Next, individual scans were cleaned of extraneous elements to the object (such as the operator's hands, walls, surface on which the object rests, and other irrelevant objects) using the *Editor* tool *Erase* offered by the software (Artec 3D 2020, 112-116). After refining the scans, those useful for alignment were selected, and a *Rigid Alignment* in two variants was performed: by drag and drop, where the scans are manually dragged and positioned as close as possible to each other, and for homologous points, where by specifying at least three relevant points present in both scans, and running the *Align* command, an alignment that also considers the coordinates of the points is performed (Artec 3D 2020, 117-124). After finishing the alignment of all the scans, it proceeded with the application of two algorithms in succession: *Global Registration*, which transforms the surfaces of each frame to correctly align them with each other (Artec 3D 2020, 130), and *Outlier removal*, which works as a filter to automatically remove extraneous fragments from the main surface (Artec 3D 2020, 112-113). As a final step, the scans were merged using the *Sharp*

*Fusion* command and did not apply automatic gap closure to obtain the most detailed RAWp as possible (Artec 3D 2020, 137-140). The RAWp obtained in this phase is not textured; for models acquired with structured light scanners, the texturing process takes place during the subsequent Modelling phase (Section 3.2.3).
On the other hand, the processing of photogrammetric data was organised into several stages (Fig. 3). Since the quality of the surface reconstruction in the photogrammetric workflow is significantly influenced by the quality of the dataset used, it was important to define a common methodology to face possible issues during data elaboration (De Paolis et al. 2020).

Before processing the dataset, an audit was carried out to verify if any adjustments to the RAW files were necessary within dedicated editing software: the main software used included Adobe Lightroom (https://www.adobe.com/it/products/photoshop-lightroom.html), Camera Raw (https://adobe-camera-raw.it.softonic.com/), and the open-source Raw Therapee (https://www.rawtherapee.com/), for correcting exposure, sharpness, highlights, shadows, and white balance. The edited images were then exported in .TIFF using LZW compression or .JPEG format. After performing a quality check on the images, the dataset was loaded into the Structure from Motion (SfM) software. For this phase, the main software tools used include Agisoft Metashape (https://www.agisoft.com/) and 3DF Zephyr (https://3dflow.net/it/software-di-fotogrammetria-3df-zephyr/) (Table 1), with Meshroom, based on the open-source AliceVision (https://alicevision.org/#meshroom) framework, currently under testing. For images acquired with a turntable, it was necessary to apply automatic or manual masks to exclude the background and isolate the object (Brandolini and Patrucco 2018; Farella et al. 2022b).

Next, the image alignment process was carried out. In this phase, the software identifies key points and tie points in the images to calculate the relative position of the cameras, generating a preliminary low-density point cloud (Sparse Point Cloud) that represents the approximate geometry of the object. In this phase, it was ensured that all images were properly aligned by examining the key points and alignment report. To proceed, the average error of < 1 pixel was considered the optimal value to ensure high accuracy in the following steps. To achieve greater accuracy in camera alignment, we used Ground Control Points (GCPs) through automatic recognition or manual assignment of coded markers within the images (Remondino 2011). The known coordinates of the markers were used when available, or manually input distances were applied to align the photogrammetric model using 3D constraints. After setting specific targets as control points and checkpoints, we moved forward with the alignment to scale and orient the model within a local reference framework. After the alignment, the checkpoints were used to verify the metric accuracy of the model. The difference between the actual coordinates of the checkpoints and those calculated by the software indicates the model's error: in this case, an RMSE error of less than 1-2 mm was considered the optimal value for medium to large-sized object models. In the case of a lack of partial alignment within problematic datasets (such as with thin or flat objects like coins), it was necessary to process data creating different workspaces and subsequently merge the separated point clouds before proceeding to mesh creation. The merging of the different point clouds was done by manual placement of common distinctive points on the images to facilitate recognition by the photogrammetry software and subsequent alignment.


*Fig. 3: From Sparse Point Cloud to Textured Mesh in 3DF Zephyr data processing.*

Once the orientation was completed, a dense point cloud was generated. This process is done by creating depth maps, which represent the distance of each pixel from the camera (Lu et al. 2018). Next, any outliers generated by reflective surfaces or incorrectly acquired areas were removed. In the case of complex situations, external software such as CloudCompare (https://www.danielgm.net/cc/) was used for more thorough cleaning (Demetrescu et al. 2020).

Based on the points in the dense point cloud, the mesh was generated. In this context, the range of polygons was chosen depending on the geometric complexity and size of the mesh involved (Table 1). The level of detail is a determinant factor for the creation of a satisfying normal map starting from the RAWp geometry for the DCHO at a later stage.

Finally, the single or multiple textures are generated. The texture is an image mapped onto the surface of the 3D model to faithfully replicate the colours, details, and surface features of the real object. In this step, the photogrammetry software uses the images acquired during the survey to project the surface details of the object onto the 3D model. This is done by associating the 3D coordinates of the model points with their positions in the 2D images using the UV mapping technique. UV mapping is the process of associating three-dimensional mesh coordinates with two-dimensional image coordinates. Each polygon in the mesh is developed (unwrapped) onto a flat surface and then applied with the texture.
For texture building, the software can employ different blending techniques to eliminate any seam lines or issues between the images (Dostal and Yamafune 2018). For problematic datasets, we used an additional masking process specifically designed for the texturing phase, excluding any reflections on the object surface within the images. Furthermore, where needed, an image weighting process was implemented to ensure a sharp texture while minimising data loss. Among the options for texture generation, the desired resolution for the image applied to the model can be specified: for the RAWp, a high-resolution texture (16K or 8K) was generated to ensure a high level of both geometric and texture detail to be used as a starting point for subsequent interventions. Finally, both 3DF Zephyr and Metashape allow the download of a processing report to keep track of key operations performed within the software and ensure more transparent data manipulation tracking (Moore et al. 2022).

### 3.2.3. Step 3: Modelling phase

The RAWp is the initial output from the photogrammetry or scanner software, representing the data processing result without any interpolation or geometry correction, except for rough data cleaning. To achieve a complete DCHO without topological issues, two primary methodologies were applied: automatic tools were used to fill small gaps, while manual intervention was performed within 3D modelling software for larger gaps and significant non-manifold issues, with authorial decisions made to ensure the result remained as faithful as possible to the original CHO.

Regarding SLS, we considered “modelling” to be the stage in which the RAWp is adjusted to obtain a closed, textured model (DCHO).

Sometimes, the complex object shape or the scanning conditions do not allow all the necessary data to be captured appropriately, and the resulting models may have local errors such as gaps. These errors were addressed directly within the Artec software before subsequent export. Using the *Fix Holes* tool, small size gaps and non complex shapes were automatically closed by the software. For holes that were too large in size or shapes that were too complex for the algorithm to close correctly, manual interventions were used to reduce and modify these gaps (e.g., the *Bridge* tool) (Artec 3D 2020, 141-151).

For holes of too high complexity, subsequent closure within 3D modelling software such as Blender was done. Once all the holes on the 3D model were closed, a check was made to assess that the reconstructed surfaces were consistent with the adjacent areas; in cases where the reconstructed edges were not sufficiently camouflaged, they were smoothed out to harmonise the surface of the 3D object (Artec 3D 2020, 145).

The last step in obtaining the DCHO was texturing. After selecting all the scans necessary for total texture reconstruction of the object and checking the *Inpaint missing texture* option, allowing the algorithm to apply the texture to regions lacking it by diffusing it from neighbouring areas, the maximum output resolution achievable by the software (16K) was set. Then, the texture application algorithm was started (Artec 3D 2020, 155-162). In cases where texture application to areas where the information was not present was not satisfying, texture correction was performed outside the scanning software, using the Texture Paint tool in Blender, Photoshop (https://www.adobe.com/uk/products/photoshop.html) or the open-source GIMP (https://www.gimp.org/) (Whitt 2023). The phases described are resumed in Figure 4.

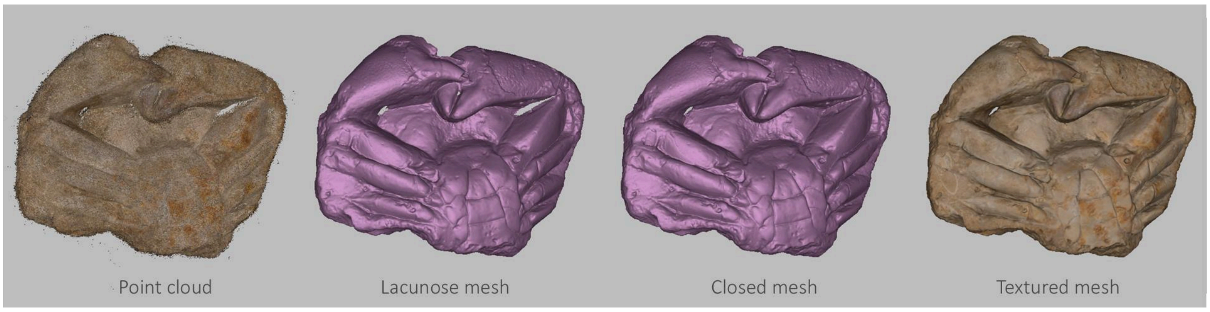


*Fig. 4. Different SLS phases from Point cloud to Textured Mesh in Artec Studio 15 Professional.*

*Fig. 5: Flying fish CHO, Museum of Palazzo Poggi, Bologna.*

Regarding the RAWp obtained from SfM photogrammetry software, the process is conceived to create a closed and complete DCHO free from geometry issues.

The most common scenario involved the RAWp containing gaps of different entities. Concerning small gaps, mesh optimisation and cleaning tools were used to optimise the mesh and correct errors. In some cases, the mesh was exported to perform minor optimisation tasks in external software, such as Meshlab (https://www.meshlab.net/) (Cignoni et al. 2011) or CloudCompare. Cleaning tools removed unnecessary or incorrectly generated triangles, and non-manifold geometry was identified and corrected to ensure proper mesh structure. Surface smoothing helped eliminate minor distortions, while gap-filling algorithms addressed holes or inconsistencies, creating a continuous surface. As for scanned RAWp, when it was not possible to solve gaps or non-manifold issues through automatic tools, a manual intervention was needed using Blender. To facilitate manual intervention with complex models, an initial geometric simplification was performed to achieve a polygon count suitable for the processing power of the hardware in use.

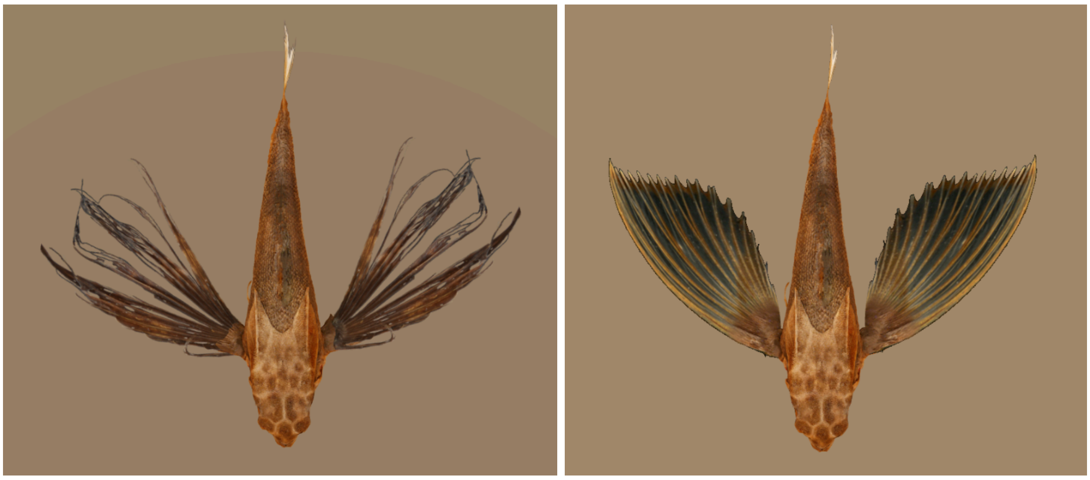

*Fig. 6: DCHOo of two different interpretations of the flying fish.*

Topological issues that needed to be addressed (mainly holes, non-manifold edges and overlapping faces) depended on several factors, including the conditions of the survey environment (e.g. shadows), the tools and methodologies used during acquisition (e.g. metrological kits), and CHOs features (e.g. occluding geometries). For example, certain items, like manuscripts, could not be handled due to their fragile condition, restricting data acquisition to their front and side. The manual editing involved authorial interventions to the mesh, aimed at restoring missing or altered details with the utmost attention to reliability and fidelity to the original asset (Table 1). These adjustments were executed using a combination of cutting tools and free-form modelling brushes, enabling the creation of geometries closely aligned with the original form. In some cases, we chose to add an additional layer of interpretation to the DCHO, illustrating the transformation and potential changes the asset underwent over time before becoming a CHO. In this context, an illustrative case is that of the flying fish CHO (Fig. 5). The fins, preserved through embalming, were in a very degraded and delicate state, giving a misleading impression of the animal's natural appearance.

*Fig. 7: Difference between RAWp and DCHO of the microscope CHO.*

After creating the DCHO of the displayed CHO, an additional DCHO was generated, replacing the embalmed fins with a representation closely resembling the fins of a live fish of the same species, depicting its appearance prior to preservation as a CHO (Fig. 6). In both cases, orthographic photos of the fins were used and projected onto a plane with an active alpha channel.

Among the DCHOs, some exceptional cases required complete remodelling of the asset due to their highly intricate geometries. When acquired through photogrammetry, these complex structures were subject to interpolation and generation of low confidence geometry, resulting in a distorted appearance. This intervention was necessary for the microscope (Fig. 7) due to its mix of non-lambertian materials (glass, metal) and complex small-scaled geometries that were challenging to capture with the available technologies, which, in the RAWp model, were automatically interpolated and resulted in an inaccurate and distorted representation of the small mechanisms (gears, levers, knobs, screws) the asset. The object was then remodelled in Blender, based on the RAWp, and the original textures were preserved through texture baking. Metalness and roughness maps were created to restore the brass's roughness lost during acquisition.

### 3.2.4 Optimisation phase

The DCHO is the model resulting from interpolation and the resolution of geometric issues generated from scanned or photogrammetry data processing. The final step required to optimise the DCHO to obtain a performant DCHOo suitable for web application and real-time interaction, while retaining an adequate level of detail and visual quality.

The DCHO went through a re-meshing process to achieve a quad-dominant topology. Remeshing was either done automatically or manually. Automatic re-meshing software like Instant Meshes (Jakob et al. 2015) converted an isotropic triangular mesh into a quad mesh by applying a unified local smoothing operator, which refined both edge directions and vertex placements in the resulting mesh (Jakob et al. 2015). This process ensured a uniform, quad-based topology and reduced polygon density to an optimised range based on the features of the objects (Tab. 1).

In manual retopology, an initial automatic re-mesh often served as a visual guide. Tools for snapping and constraint-based editing helped align vertices and edges to the underlying geometry, particularly in areas with complex curvature. After establishing guiding polygon strips, these strips were extended and connected using bridging techniques along principal curvature directions. This iterative process continuously evaluated connectivity and curvature, often integrating sculpting tools to refine intricate details.

In the case of automatic remeshing, the mesh was checked for defects, with adjustments made where necessary, and complex parts were verified to ensure they had not been excessively simplified compared to their original structure. Proper edge loop connectivity and placement were also managed to ensure visual quality and accurate mesh deformation, with sculpting tools applied for further refinement.

Despite manual retopology being the best method for achieving mesh control on details and highly optimised geometric models, it is undoubtedly the most time-consuming approach. Given the project's limited timeline and scope, automated re-meshing was selected as the standard procedure for most assets. In this case, manual interventions were made where the automatic tool did not achieve satisfactory results in the thinner or more complex parts of the mesh. This choice still provided a satisfactory level of performance for web-based publication and real-time interaction, balancing efficiency and quality for the project's goals (Fig. 8).

Following re-meshing was necessary the creation of a new UV map to preserve texture integrity. The new UV map was created manually, with seams, and lines along which the mesh is "cut" for laying it out in 2D, and carefully placed in key areas to ensure precise and controlled texture mapping (Fig. 9). Following seam selection, the model undergoes unwrapping, where it is "opened" along the seams to produce UV islands, or separate polygon groups representing sections of the mesh. After unwrapping, UV layout adjustments are applied, ensuring no UV islands overlap and adjusting the Texel Density, to increase the resolution in areas of the model that require higher visual detail. Texel Density is a measure that represents the resolution of a texture in relation to the size of a 3D object and is directly influenced by the GSD of the photos used to generate the texture. More specifically, it indicates how many "texels" (single units of texture space) are applied per unit area of the object's surface.

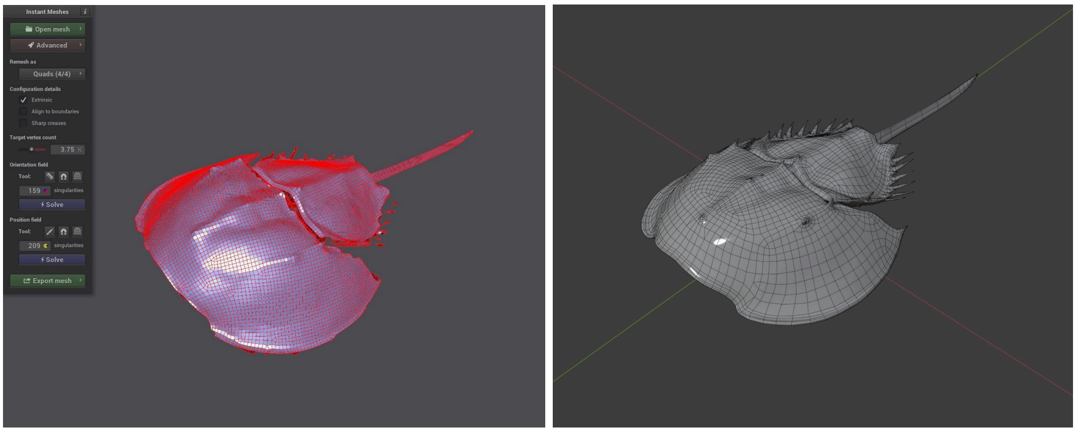


*Fig. 8: Comparison between automatic retopology with Instant Meshes and manual retopology on Horseshoe crab.*

*Fig. 9: Difference between UV maps and textures of the Owl Volume before and after the intervention.*

This approach proved especially beneficial for objects with prioritised details, such as books, allowing for the enlargement of specific UV faces to capture fine details and achieve a well-organised texture layout (Balzani et al. 2024).

After the creation of a balanced UV set, prioritising the most relevant parts of the mesh, we proceeded with texture building. For 3D models obtained through photogrammetric techniques, SfM software can re-project the textures obtained during the generation of the RAWp onto the DCHOo provided with the new UV map. Alternatively, a new texture can be generated using photos from the original dataset.

As concerns 3D models obtained from structured-light scanners, the textures were baked into Blender from the DCHO onto the DCHOo. The baking process involved simulating the characteristics of the high-poly mesh model (such as geometry, depth, colour, and texture), and transferring them onto the low-poly mesh model (DCHOo) (Apollonio et al. 2021).

In some cases, where there were gaps in the texture or visible UV seams, issues were resolved by directly editing the image using software like Photoshop or GIMP. Additional modifications were made directly in Blender using the texture paint tool. Once a complete and sharp texture was obtained, PBR (Physically Based Rendering) maps (Farella et al. 2022b) were created (e.g. roughness, metalness, normal, and ambient occlusion (AO) depending on the specific cases. The main aim consists in achieving realistic simulation of light interaction with surfaces. The roughness map defines surface smoothness or roughness, regulating reflection intensity: white indicates a rough surface, while black represents a smooth one. The metalness map distinguishes between metallic (white) and non-metallic (black) materials, enabling standardised reflection management (Farella et al. 2022b). Normal maps simulate detailed textures on low-poly models by transferring high-poly geometry through a "baking" process using software like Blender or Substance Painter. Alternatively, the normal map can be exported directly from the photogrammetry software in the case of models obtained through photogrammetric acquisition. Finally, the ambient occlusion (AO) map improves realism by simulating soft shadows in concave areas, improving depth perception. Each map can be created or refined in software like Photoshop, GIMP, Materialize (https://materializecss.com/), or advanced texturing tools, such as the TexTools plugin (https://github.com/franMarz/TexTools-Blender), enabling precise control over the final appearance of the 3D model.

The DCHOo model is thus designed to balance visual fidelity with performance, making it ideal for applications requiring rapid rendering and reduced resource demands, such as the ATON framework. At this stage, to enable even more efficient performance of the DCHOo, the textures were optimised to 4K, with PBR maps resized to 4K or 2K depending on specific cases; multiple textures associated with a single asset were baked resulting in a single 4K map for each DCHOo (Table 1).

### 3.2.5. Step 5: Export phase

Each 3D model obtained during the workflow was exported in a specific format. Both the RAWp and the DCHO were exported from Blender in OBJ or FBX format, which allows for the preservation of the maximum texture resolution, ensuring that visual fidelity is maintained in the final output. OBJ has been the first choice, being an open-source format, but in the case of complex 3D models that required features non-supported by OBJ such as multiple UVs, vertex weights and others, FBX was used instead.

On the other hand, the DCHOo is exported exclusively in the glTF format, which is particularly advantageous for sharing and interactive navigation of 3D objects within Web3D applications. glTF is a standardised format that facilitates efficient transmission and rendering of 3D models, making it ideal for real time visualisation on Web3D applications. It supports various features, including PBR materials (Robinete et al. 2014).

Throughout the export process, we adhered to a set of specific guidelines (https://osiris.itabc.cnr.it/aton/index.php/tutorials/creating-3d-content-for-aton/exporting-3d-models-from-blender/) tailored to the Web3D platform employed in this project. These instructions were developed to ensure compatibility and optimal performance within the target application, addressing considerations such as geometry optimisation, material settings, and texture mapping. By following these guidelines, we aimed to enhance the usability and accessibility of the 3D models in a web context, thus supporting interactive engagement and exploration by users. This approach underscores the importance of format selection and export procedures in the development of high-quality 3D assets for digital environments.

### 3.2.6. Step 6a: Metadata creation phase

The creation of metadata is a process composed of several substeps, which are partially independent and partially overlapping with other phases of the workflow. The process is structured so that the creation and gathering of the data can be simple and intuitive, as well as collaborative, as digitisation often happens in parallel. Concerning the choice of the tool for the task, Google Spreadsheet is a valuable option for real-time joint contributions: the importance of this feature is also related to guaranteeing the coherence of the values of the fields. It is possible to divide the metadata into two main groups: bibliographic or catalographic data, concerning the physical cultural heritage objects included in the exhibition, and the process data about the acquisition and digitisation process aimed at the creation of the related RAW, RAWp, DCHO and DCHOo. These two datasets are collected in two separate spreadsheets in tabular format, whose fields should be clearly defined to allow a metadata crosswalk to an RDF conversion, according to a chosen or defined Application Profile. To proceed with the following steps of the metadata management process, the tables are exported in CSV format. For compliance with the Open Science principles, the datasets should be published on platforms that allow open access to them, such as Zenodo.

To perform the conversion, Morph-KGC - software mentioned in the literature review - was extended (https://github.com/dharc-org/morph-kgc-changes-metadata) to meet the requirements imposed by the defined workflow. The tool is open source and available on GitHub, and its main components are:

1. Mapping Files. A YARRRML (https://rml.io/yarrrml/) file is compiled for each of the datasets, defining the mapping rules for converting the input information in RDF triples, according to the Application Profile. Once the rules are defined, the mapping file can be reused for converting data of any CSV following the same structure as the initial one.
2. Configuration file. This is a .ini file in which the parameter values for the conversion of the input datasets are set. The README.md file of the software extension provides further guidance about the field values to define. The file is divided in sections introduced by their key, stated in squared brackets. The general section contains both mandatory and optional parameters, including the name of the output file, its format, and the directory in which the file is going to be stored. Each dataset to be converted, in this case two, has its subsection, in which the path to the correct mapping file is declared, as well as the input path.
3. User-defined functions. Morph-KGC provides built-in functions, which translate the original RML ones, declared in Java. In the same file, it is possible to add user-defined functions for handling specific needs determined by more complex input dataset structures, although the coverage of the built-in functions is quite extensive and addresses the majority of the issues encountered by the average users. and interpreting complex data. These are declarative transformation functions implemented through the RML Function Mapping Language (RML-FNML) (Arenas-Guerrero et al. 2024b).
4. Launch script. A Python file to be run to execute the process. In addition to orchestrating the conversion process, this file can also be exploited to perform some data preprocessing, which can make the mapping activities smoother by allowing the reuse of predefined built-in functions instead of defining new user-defined ones to address specific necessities. Similarly, although it should not be necessary, some post-processing tasks can be performed on the produced output, in case minor formal inconsistencies are spotted. This latter procedure is discouraged since the tool is extensively documented to allow the user to benefit from the multiple conversion solutions offered.

### 3.2.7. Step 6b: Provenance creation phase

The Provenance creation phase implements systematic tracking of metadata record changes through the OpenCitations Data Model (OCDM) (Daquino et al. 2020). This approach creates detailed "snapshots" whenever an entity undergoes creation or modification, with each snapshot preserved in a dedicated provenance graph to document the entity's state at that specific moment.

The data model establishes clear relationships between entities and their snapshots using semantic properties: snapshots (categorised as `prov:Entity`) connect to their source entities via `prov:specializationOf`. Critical temporal data is captured through `prov:generatedAtTime` and `prov:invalidatedAtTime` timestamps, marking creation and invalidation points respectively. Attribution and accountability are maintained by recording responsible parties through `prov:wasAttributedTo`, while `prov:hasPrimarySource` establishes information lineage back to original sources. The evolution chain between snapshots is preserved using `prov:wasDerivedFrom` relationships.

OCDM enhances the base Provenance Ontology (PROV-O) (Lebo et al. 2013) capabilities by introducing `oco:hasUpdateQuery` (Peroni et al. 2016). This extension enables detailed tracking of RDF graph modifications through SPARQL `INSERT` and `DELETE` operations, making it possible to reconstruct previous entity states by reversing subsequent changes.

Incorporating this provenance tracking system into the broader Metadata creation workflow significantly enhances the FAIR principles compliance for both Digital Cultural Heritage Objects (DCHOs) and their associated data. The comprehensive documentation of changes and authorship creates a reliable foundation for research applications by ensuring authenticity and enabling confident reuse across different contexts.

### 3.2.8. Step 7: Presentation phase

In order to make DCHOs accessible on the web, the final step is to employ Web3D technologies offering an interactive presentation layer to final users. In this phase, optimised DCHOs are transferred from local storage to dedicated server-side storage, converted into Web3D interoperable standards (see Related Work section).

In our case, the open-source framework ATON - designed and developed by the CNR ISPC in 2016 (Fanini et al. 2021) - is adopted. ATON is built on large open-source ecosystems such as Three.js (https://threejs.org/) and Node.js (https://nodejs.org/) and solid web standards to provide accessible alternatives for organisations, labs, researchers, developers, and museums looking to design and implement cross-device Web3D/WebXR applications specifically for the Cultural Heritage sector.

Single 3D items can be uploaded by different professionals into a dedicated presentation node, using a multitude of approaches to populate digital collections. In our case, the open-source cloud service NextCloud (https://nextcloud.com/) was adopted for the data layer, allowing easy management by the 3D modelling and content creators team.

ATON uses scene descriptors – similar to Smithsonian Voyager SVX (https://smithsonian.github.io/dpo-voyager/document/) – to reference 3D items in collections and their hierarchies, with lighting setups, viewpoints, semantic annotations and much more. Each scene in ATON has a unique (alphanumeric) ID assigned, thus providing persistent identifiers: this is ideal for 3D galleries in online virtual museums (VMs) or digital libraries. Published 3D scenes can also be accessed or referenced by any ATON Web3D/WebXR application deployed on the same instance.

## 3.3 Toward the digital twin

### 3.3.1 Environment 360 documentation

Given the exhibition's temporary nature, a crucial aspect of effective post-processing involved meticulously documenting the curated spaces and spatial placement of objects to preserve the intended narrative from a curatorial standpoint. Before returning certain pieces to their institutions of origin, we opted to create a basic mock-up using 360° panoramic views of the exhibition. This approach provided a common reference point for the creation of the digital twin. Using 360° panoramas for creating a Virtual Tour was the most efficient solution that has gained traction among museum institutions in recent years for a range of applications, including enhancement and documentation of cultural heritage (Wu 2022).

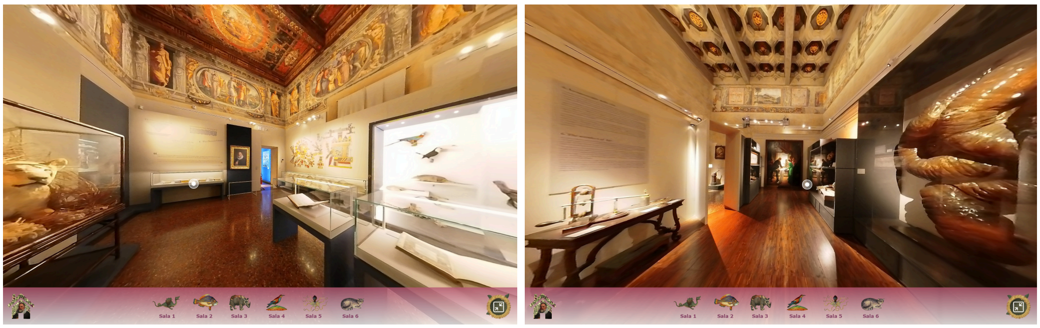

*Fig. 10: Example of UI of the virtual tour navigation mode designed by the Skin Editor tool.*

For the Aldrovandi exhibition, we used 360-degree spherical or equirectangular images captured in each room, as this proved to be the most effective solution for providing comprehensive information. As high-resolution images were unnecessary for our purposes, we opted for a quicker method using the Insta360 ONE X2, a dual-lens 360 action camera designed to capture panoramic images and videos up to 5.7K. Our plan involved capturing multiple panoramas in each room, enabling a virtual tour that follows the standard visitor path and aligns with the audio guide available during the exhibition. During image capture, we were able to instantly review the results on a tablet via the Insta360 Studio mobile app, connected to the camera over Wi-Fi. This approach reduced time and helped prevent potential errors such as visitor presence in photos. The images were then edited and exported at the highest available resolution, resulting in 360-degree images of 6080 × 3040 pixels. Each individual panorama was uploaded to a shared cloud platform, and the various shots were interconnected to simulate guided, one-way navigation through the spaces. This process, which created the interactive Virtual Tour, was completed using Pano2VR (https://ggnome.com/pano2vr/). The primary function of this tool (Cao 2022) is to transform panoramic images into web-compatible formats (HTML5/CSS3) suitable for various platforms. By importing panoramic images into the software, users can link them together to recreate the exhibition's path. The tour can be enhanced with interactive features such as photographic hotspots, directional audio, informational pop-ups, and video elements. Additionally, the user interface is customisable using simple CSS through the Skin Editor (Fig. 10), allowing for tailored formatting and visual styling.

### 3.3.2 Environment 3D modelling

One of the final stages in creating a digital twin for the temporary exhibition involves the meticulous reconstruction of the display spaces for each exhibit item. This process not only includes recreating the walls, floors and ceilings of the exhibition hall but also the precise replication of display cases, panels, and captions that accompanied each item in the physical exhibition. The re-creation of the rooms is a multi-faceted process that requires various techniques and specialised software to achieve a realistic digital replica.

The first step was the photogrammetric acquisition of the ceiling and parts of the walls where frescoes are preserved. The RAW data were acquired using photogrammetric techniques. Images obtained from this process were processed in 3DF Zephyr software. The RAWp obtained (Fig. 11) was then imported into Blender where it was rotated and scaled to align correctly with the intended exhibition layout. This initial adjustment allowed us to proceed to the next steps of detailed modelling and optimisation.

Thus, a manual modelling was performed in Blender for reconstructing the ceiling and walls to achieve a mesh as low-poly as possible. The manual modelling process used the RAWp as a foundational reference. Since ceilings are composed by assembling repetitive elements such as trusses and decorations, the ceiling was reconstructed by modelling a smaller section that was later duplicated using the Mirror and Clone modifier in Blender to achieve symmetry: though the mirror modification was only finalised at the end of the baking process.

At this first step, the geometry has been modelled as perfectly regular and without modifications in order to simplify the UV mapping and to get identical UV islands so that at a later stage, eventual missing parts could be sampled by other instances of the same module. Then simple deformations have been applied both to match the real geometry of the design and to account for deformations such as truss bending and similar.

*Fig. 11: RAWp of the ceiling imported in Blender.*

At this point, the texture and normal maps were baked, following a process similar to the one used during the optimisation phase of the assets. The diffuse and normal maps were both baked directly in Blender. The normal map, in particular, was used to recover fine details and subtle reliefs in the ceiling decoration that had been lost during the modelling phase. Any gaps or imperfections in the resulting model were addressed using Blender's texture paint tools, or the GIMP editing software. This has been made possible by having built the maps on a regularised and straightened version of the ceilings, so that the resulting UV islands are regular and allow for direct editing within a software for processing raster maps.

After completing the ceiling (Fig. 12), the next step was to recreate the room's walls by starting with a basic geometric shape and adjusting it to match the dimensions of the DCHO. Once aligned, a precise UV map was generated to enable the baking of a new texture. This texture was then refined and enhanced in GIMP to better fit the walls, improve colour quality, and fill in any missing sections. The missing parts were added through a cut-and-paste process, utilising orthogonal photos taken during the photogrammetric acquisition phase. This final process is particularly useful when it is not possible to achieve new texturing through reprojection in photogrammetric software or by baking, especially when there are missing sections in the geometry. In this case it could be also necessary to add synthetic material to the missing parts and finalise the texture with the final baking, as we will see later.

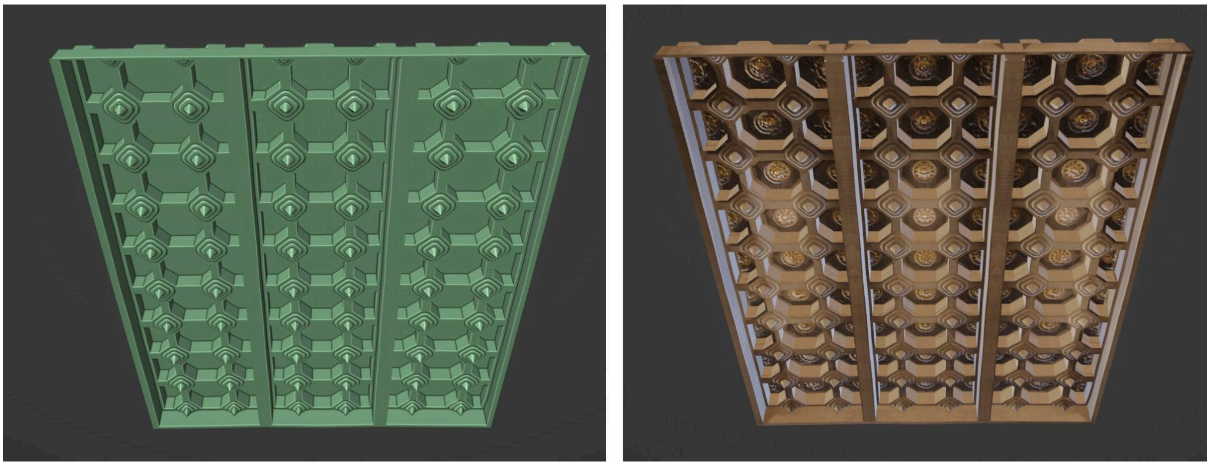

*Fig. 12: Modelling and texturing the ceiling.*

The second phase of recreating the exhibition environment involved manually constructing each display case and exhibition panel. To achieve the highest level of accuracy, we relied on the floor plans and elevations provided in the original museum exhibition design. These documents included detailed specifications of the room dimensions, as well as the height, depth, shape, and content of the display cases. For this process, photographs and videos taken during the acquisition phases were essential to understand the position of each element of the scene, allowing for a faithful reproduction of the original setup.

*Fig. 13: View of Room 6 exported in glTF format after baking the lighting.*

At the end of the creation process, each element within the scene has been associated with its own synthetic material that accurately reflects those of the physical exhibition. For example, the metal material for the display cases was created either using an online resource like Poly Haven (https://polyhaven.com/), which provides realistic textures for download or by appropriately applying colours and textures acquired from the actual environment and set-up, such as the Venetian floor material or the displays with their graphics. Since synthetic materials define the behaviour of the material itself when interacting with light, the rendered colours, reflections, refractions and other complex behaviours are locally dependent on the synthetic illumination.

In the final baking process (Apollonio and Giovannini 2015), these elements are unified, resulting in a single, cohesive texture that accounts for the resulting interaction between original materials under the given illumination in the synthetic scene, which mimics the real one. This strategy overcomes the limitations in terms of photorealism in present time Web3D applications, that cannot make such complex calculations in Real Time. The baking process consents to pre-calculate such interactions and to re-apply to the objects the resulting shading just as a simple colour texture.

Glass surfaces, such as those of the display cases, required specific adjustments to replicate the transparency, reflectivity, and refraction that would allow viewers to see the objects inside. Achieving this involved using different parameters: the Displacement settings were modified by incorporating a Noise Texture to add subtle surface variations, and both Alpha and Roughness channels were adjusted to reach the right balance between clarity and natural light diffusion. In this way, the final rendering achieves the correct glass transparency. This process contributes to a more immersive scene, where the glass surfaces not only look visually realistic but also interact naturally with the light and surrounding environment.

To finalise the recreation of the exhibition's digital environment, accurate lighting placement was essential. Each light source was positioned to simulate the actual setup in the original exhibition space, including direction, intensity, and colour temperature, which were adjusted to match those of the physical room. Following this, the lighting was baked into the scene, capturing shadows and reflections, in order to maintain the level of realism in the lighting without overloading the scene. To bake the room's lights and shadows directly onto the texture, the room was divided into several sections (e.g., ceiling, walls, floor, panels, display cases). For elements that did not require roughness, reflections, transparency, or other specific characteristics, a Diffuse bake was performed, allowing the texture to incorporate the room's lighting effects in a uniform way. For elements with transparent or reflective parts (such as display cases), a Combined bake was used to retain the mentioned physical characteristics. After the baking process, the room was exported as a single glTF file with a reduced number of 4K textures (Fig. 13).

### 3.3.3 Final Optimisation

After recreating the spaces of the temporary exhibition, it was necessary to produce a further optimised version of the environment and each asset within it, to combine all individually generated elements into a single scene to enable fluent user navigation. The optimisation was carried out simultaneously for each of the six rooms that hosted the exhibition.

As for the environment, no geometric optimisation was needed: the output of the manual modelling for each room was a low-poly mesh created from simple shapes. The situation was different, however, for the textures. After light-baking, which was done to recreate shadows and ambient lighting directly on the textures, an additional baking process was required to merge the room's multiple textures into as few maps as possible at 2K or 4K resolution each. The goal of baking, as in other cases, is to optimise the performance of the 3D model as much as possible, yet maintain acceptable resolution quality depending on the contexts of reuse.

On the asset side, however, optimisations on each DCHOo have been made from both a geometric and texture perspective to obtain a *placeholder* model (PL). This additional version is needed to create a performant immersive environment for the user's exploration, where all the elements coexist in the same scene. Starting from the DCHOo, the further geometry optimisation to obtain the PL was done through two main methodologies: polygon decimation using Blender, or remeshing using Instant Meshes (Jakob et al. 2015). In both cases, the goal was to reduce the number of polygons as much as possible (Fig. 14). While internal decimation does not affect the UV map, remeshing requires a new UV mapping, followed by transferring the DCHOo texture to PL through baking.

*Fig. 14: Example of PL starting from the re-meshing of the DCHOo.*

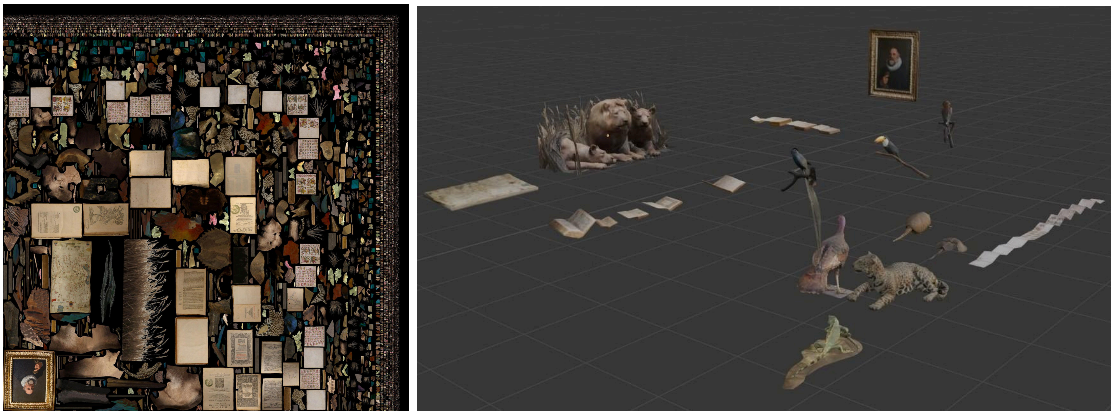

*Fig. 15: Texture map (left) obtained from the texture baking of all PL in Room 1 (right).*

Regarding texture optimisation, DCHOos textures for each room were optimised into a single 4K map through baking, then assigned as the only material of a single mesh including all DCHOos. For example, if the first room contains 21 assets, each with a 4K texture, the final optimisation output involves merging the 21 meshes into a single mesh. This mesh is assigned a single material with one 4K map, created by baking the 21 pre-existing maps into one (Fig. 15). The overall process of final optimisation was conceived for creating the optimal conditions to facilitate the web-based and immersive implementation for real-time performances.

### 3.3.4 Web-based and immersive implementation

A digital twin application has been designed to create a fully explorable virtual replica of the temporary exhibition. To achieve a minimum viable product (MVP), core features were defined, including user navigation, high-quality exhibit exploration, and a clear presentation of exhibit's metadata. A functional prototype was developed following a UI/UX study.

The exhibition consists of a number (six) connected rooms, navigable one by one through interactive doors. The user journey begins at a specific start point of the first room, with a welcome screen launching an audio guide to introduce the overall exhibition. Within the virtual environment, the user can navigate the exhibition space freely using the teleport tool (Bozgeyikli et al. 2016), viewing all the exhibits placed in cases and the graphics displayed on the room's walls. Interacting with the single exhibit, the user can explore it in detail, visualising the high-quality version and metadata.

A prototype has been designed as a web-application accessible on both handheld devices and VR headsets without installation, offering an embodied exploration in Virtual Reality and a flexible interface via desktop / tablet / touchscreen devices. Built using ATON, the web-app takes advantage of the web-based, VR-ready 3D features of the framework. Although the process is streamlined by using ATON's API, ensuring a convenient tradeoff between performance and quality presented technical challenges involving optimisation of 3D assets and a tailored 3D scene management strategy too.

With a scalable approach in mind, the browser's memory usage has been optimised by loading in the virtual environment only one room and its exhibits at a time, to avoid overloading the client's device and managing an un-predetermined set of exhibition's rooms. To allow users to view the entire collection placed in the room and appreciate each object in detail, two complementary exploration modes were implemented:

1. Room exploration: In this mode, the user can explore a scene with two main elements: the room (with its materials and textures) and the collection of exhibits. Low-poly versions of all objects are used, with meshes merged and textures baked into one or two files. This optimisation reduces draw calls and texture loading, speeding up load times and allowing more exhibits to be managed within each room.
2. Exhibit inspection: From room exploration, users can click on an exhibit to view it in detail. Selection is triggered by simple clickable cubes, moving the user to a close-up viewpoint. After this transition, the low-poly room and exhibit collection are unloaded to free memory, and a high-quality version of the selected object is displayed. The positions of the low- and high-poly versions are carefully aligned to maintain visual consistency, while metadata for the exhibit appears on the side of the screen.

This approach balances graphic quality with performance, providing an efficient user experience. Core features were tested with real users, revealing that the switch gesture between room exploration and exhibit inspection works without disorientation, even if a short delay is needed for loading the asset. However, this gesture can cause motion sickness in VR, where maintaining a consistent user position is essential. This issue warranted an alternative design of the VR logic, which is currently being developed.

Future improvements will include integrating MELODY-based API for metadata, and experimenting with Level of Detail (LOD) (https://threejs.org/docs/#api/en/objects/LOD), 3D tiles (https://cesium.com/why-cesium/3d-tiles/) and other techniques to improve performance and reduce optimisation time for 3D assets. Real-time lighting and advanced post-processing effects are also under consideration for enhanced visual quality.

## 3.4. Software for human-readable documentation and narratives

To quantitatively analyse and visualise aggregated data, we use MELODY, an open-source, web-based platform designed to visualise and narrate Linked Open Data (Renda et al. 2023a). This tool serves as a bridge between technical data exploration and user-friendly storytelling, where narratives can capture historical contexts, provenance, and thematic elements. MELODY was initially designed using a hybrid methodology that combines eXtreme Design (XD) with Design Thinking, guiding the tool's development from ontology-driven data requirements to a UI/UX structure that supports a diverse range of storytelling elements (Renda et al. 2023b). This method not only allowed MELODY to address complex cultural heritage use cases but also ensured flexibility for other domains where structured storytelling is needed.

In particular, MELODY allows users to explore one or more Linked Open Data sources via SPARQL queries. The results of these queries are linked to various User Interface (UI) components, such as charts, maps, graphs, text searches, and tables. These components can be selected, added, rearranged, and displayed on a canvas, allowing the data story creator to alternate between visualisations and curated text, thus contextualising charts and offering interpretative insights. The final data story, as well as each user interface (UI) component, can be exported and embedded in other web pages. Data storytelling options are available to both data curators, who can select appropriate (dynamic) visualisations to be included in the digital library, and to end users, who can explore the chosen dataset via MELODY online platform (https://projects.dharc.unibo.it/melody/) and publish their own data stories in a dedicated catalogue (https://melody-data.github.io/stories/).

The choice of MELODY was guided by its open-access nature, with code and documentation available online (https://github.com/polifonia-project/dashboard), and its use of standard technologies and frameworks, making it easily extendable and reusable across different contexts. MELODY is developed as a Python application using the Flask framework (https://flask.palletsprojects.com), configured through a JSON file. This file contains background information and SPARQL queries necessary to retrieve data for the data stories, which are presented in a web interface served as HTML pages. Each data story comprises React components (https://react.dev/) that can be combined as desired during the data story creation process.

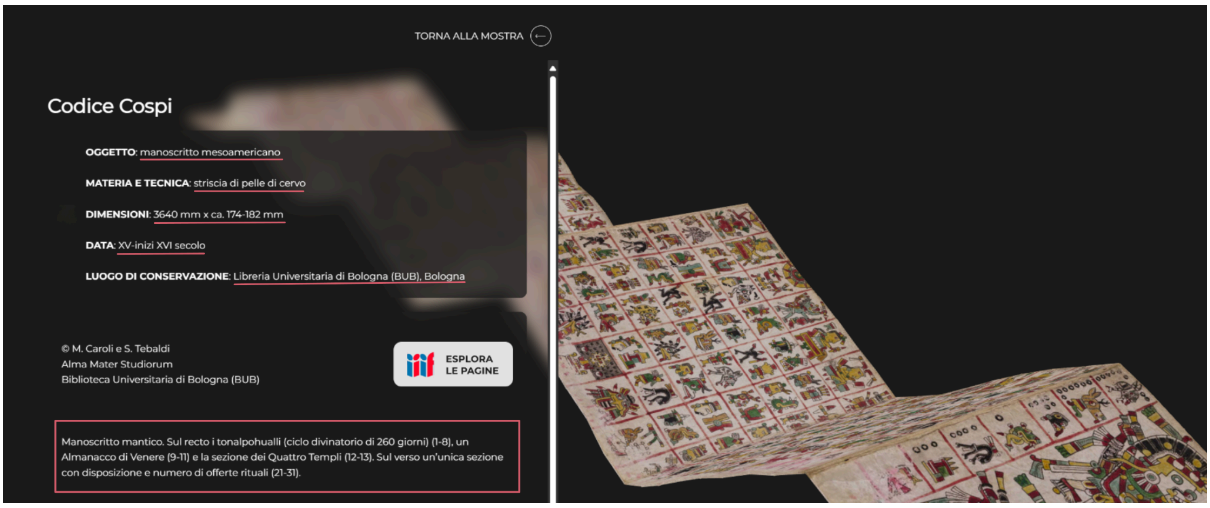


*Fig. 16: A mockup example of a MELODY API's response integrated in the sidebar of a 3D object.*

To address the needs of our pilot study, we are extending MELODY to include a new API to enhance interoperability and reuse. Specifically, this API will allow direct communication with ATON. As discussed in Section 3.3, within the ATON framework, each cultural object is visualised in a 3D environment. Upon selecting an object, an embedded iframe sends an HTTP request containing the object's unique global persistent identifier and a configuration file's location. This configuration file, in JSON format, specifies which information to display, including SPARQL queries for data retrieval, textual descriptions with object-specific data, visual elements, and additional files for styling and interactivity. The API processes these parameters and delivers a customised HTML response, which is displayed as complementary information to the object (Fig. 16).

In Figure 16, the highlighted sections represent dynamic content that changes based on the object identifier. This includes details such as the type of object, materials and techniques used, dimensions, historical period, place of conservation, and a brief description. The goal is to provide visitors with comprehensive metadata about the object and insights into the digitisation process. This approach ensures that users interacting with the digital twin not only learn about the artefact but also gain an understanding of the technical and methodological steps involved in its digital capture.

## 3.5 Interoperability and sustainable reuse with open technologies and standard formats

The final goal of the project was to use open technologies and software at each stage of the process to maximise the workflow's adaptability for reuse in various scenarios, both within and beyond Spoke 4. While metadata management did not present challenges in this regard, handling 3D models did. We carefully selected open-source software for every feasible step; however, proprietary software was necessary for certain specific tasks where open-source options did not yield satisfactory results.

To avoid dependency on proprietary software, we prioritised the use of standard formats for all types of research data generated. These formats included 3D models (such as glTF, GLB, OBJ, MTL, PNG, JPG, TIFF, E57), images (PNG, TIFF, RAW, JPG), video (MOV, MP4), and audio (MP3). These format choices were documented and, in some cases, guided by the project's Data Management Plan (Gualandi and Peroni 2024).

We advocated for the adoption of glTF as the primary 3D format, an open standard designed for interactive Web3D applications, to ensure strong interoperability with current 3D platforms and services. This choice also supports the reusability and integration of licensing information directly within the format (Robinete et al. 2018).

Specific attention was also paid to the compatibility of the chosen formats with the existing technological ecosystem, particularly with widely used online repositories and Web3D viewers. This ensured that the processed assets could be optimally employed in the chosen framework (ATON) and the target application within the flow, but also potentially published as mere assets on existing platforms. While it is true that ATON implicitly incorporates a similar instance by design, it is nevertheless considered significant to make this methodological approach explicit. In the same vein, the identification of the formats to be adopted was not based on a mere evaluation of efficacy concerning the various technical criteria such as compactness or supported features, but also on the current dissemination and documentation in an attempt to find an equilibrium between the two requirements, which were, moreover, found to be to a certain extent in conflict with each other.

The final stages of the project are still underway. At the time of writing, the 3D models, along with their associated data and metadata, have yet to be deposited in a repository for long-term preservation. The team has opted to use Zenodo, a general-purpose repository, at least temporarily, until a more specialised platform becomes available. Although Zenodo is not tailored specifically for 3D or cultural heritage data and metadata, it provides a DOI for each deposited item, supports high-level metadata schemas (DataCite Metadata Schema, Dublin Core), and is well-regarded within the research community. Zenodo was chosen for its alignment with Open Science principles, its familiarity to all project partners, its independence from the institutions involved, and its capability to host a dedicated community for the CHANGES - Spoke 4 project. This enables us to consolidate all project outputs under one umbrella rather than dispersing them across multiple repositories.

# 4. Discussion

## 4.1 Towards an open, reproducible, and transparent workflow

In moving forward with this study, a key focus will involve enhancing the informational complexity associated with the geometry of 3D objects. This means not just capturing and representing geometric and texture details but also incorporating metadata that provides a nuanced understanding of the certainty and quality of the reconstructions. This is particularly relevant because the process of digitisation is inherently imperfect. Whether due to technological limitations or data collection constraints, reconstructed objects often exhibit gaps, inaccuracies, or poorly inferred geometric features.

To address these imperfections, it is imperative to complement automatic reconstruction with the manual interventions that have been briefly recalled in the workflow. However, manual integration carries a degree of subjectivity and arbitrariness, even when it is guided by supplementary references or supporting evidence. This blending of automated and manual processes is well illustrated by the RAWp and DCHO distinction, which underscores a systematic approach grounded first in objective data capture and subsequently in informed interpretative efforts. Such a framework aligns closely with practices in archaeological virtual reconstructions where integrating missing elements demands a delicate balance of data-driven accuracy and informed conjecture.

The proposed future direction borrows the results that the scientific literature has consolidated concerning virtual archaeological reconstructions. Grounded by foundational guidelines such as the London Charter (2009), which outlines principles for the use of 3D visualisations in cultural heritage research and preservation, and the Sevilla Principles (Bendicho et al. 2013), which extend these guidelines specifically to digital and computer-based representations, this work will draw on a well-defined methodological and ethical framework.

A critical aspect of this future work is the practical application of the "Paradata" concept, (Bentkowska et al. 2012) which focuses on documenting the processes, decisions, and contextual reasoning behind the act of integrating missing parts into 3D reconstructions, offering transparency and insight into the reconstruction process. In this vein, key studies such as those by Apollonio and Giovannini (2015) applied the concept of paradata to a real-world archaeological scenario, illustrating its utility for assessing and communicating the levels of uncertainty inherent in such reconstructions.

This application provides a solid basis for transposing the same approach into our scenario, where instead of the ground truth of the surveyed data there are the portions of the real objects that have been correctly digitised, and instead of the missing parts of the archaeological remains there are the manually filled gaps with various levels of certainty.

The initial step in advancing this approach will be to create a simplified ontology of paradata specifically tailored to the digitisation of CHOs. This ontology would serve as a framework for capturing, structuring, and communicating the reasoning, data sources, and interpretative decisions made during digitisation and reconstruction. Following the establishment of this ontology, it will be necessary to identify and describe appropriate methodologies for its practical application, i.e. choosing the most suitable techniques, features and tools provided by software that would seamlessly integrate within the consolidated workflow proposed in this paper.

In keeping with the aim of ensuring maximum workflow affinity with the FAIR principles, the implementation of open-source software and formats should be improved by updating the workflow accordingly as plausible solid alternatives emerge. Concerning the latter, while glTF is at the same time an open format and the best choice for delivering 3D assets to Web3D applications, there is still no valid available alternative to FBX for a free authoring format whenever the 3D assets require advanced features that are not supported by OBJ. DAE failed to fill this gap since its diffusion remained limited and is further decreasing, while USD might soon succeed if current challenges to a wider adoption were removed. Among these, are its inherent complexity, partial standardisation across software, and potential performance issues due to dependencies. Additionally, USD might imply a steeper learning curve and its integration difficulties with legacy systems, coupled with the need for ongoing support and customisation, further complicate its seamless integration into existing workflows.

Finally, regarding software, the GLAM sector's need to adopt increasingly accessible digitisation workflows (both in terms of cost and technical skills) makes the use of open-source software at every stage of the process a significant consideration. For most stages of the workflow, open-source alternatives appear suitable; however, data processing remains an exception. As noted, in this stage, open-source options in both scanning and photogrammetry currently do not provide functions and results comparable to those of proprietary software (Rahaman and Champion 2019). In our specific case, we tested Meshroom as an open-source alternative for processing photogrammetric data, which to date confirmed the observations in the literature. As for structured-light scanner digitisation, there is potential to explore open-source alternatives in the future (e.g., Open Scan, 3DUNDERWORLD-SLS), with the aim of enhancing interoperability for equipment that is already difficult for the GLAM sector to access.

In this context, a commercially available software, Reality Capture, now offers a free version that is highly relevant for both photogrammetry and LiDAR data. This platform allows users to combine photographs with LiDAR data or meshes from 3D scanners, leveraging both input types to create highly accurate models. At the moment, Reality Capture does not natively support data from structured-light scanners: the data may need to be processed or converted into a compatible format before it can be imported. The free version of Reality Capture is available for students, educators, hobbyists, and companies with an annual gross revenue under $1 million USD. Given these advantages, we are considering a shift towards this type of alternative (at least for photogrammetry data processing), which combines processing speed, precision, and functionality, offering results comparable to proprietary software used in our pipeline.

## 4.2. Embedding metadata into DCHO and DCHOo

As previously described, specific formats involved in our pipeline - especially open specifications - allow extensibility and enrichment. This is particularly important for custom metadata, and general injection of attributes directly into the 3D format. The need to embed semantic information describing virtual products became more and more crucial in recent years, especially in the 3D Commerce (3DC) sector. 3D assets that contain descriptive and administrative metadata such as product descriptions, details on intellectual property rights, creation and modification dates and other detailed authoring history, enable the management of 3D virtual product catalogues, as well as the sharing of assets between vendors, retailers and end user platforms at industrial scale.

Within delivery formats such as glTF, this is being addressed by Khronos extensions such as *KHR_xmp_json_ld* (https://github.com/KhronosGroup/glTF/blob/main/extensions/2.0/Khronos/KHR_xmp_json_ld/README.md) that adds support for XMP (Extensible Metadata Platform) (ISO 16684-1) metadata for glTF. This replaces the original *KHR_xmp* extension proposed by Adobe in 2019. Metadata is used to transmit information such as attribution, licensing, creation date, etc. associated with the glTF asset - and it has indeed no normative effect on the asset appearance and rendering. Other platforms, such as SketchFab, may also inject custom data into the “extras” entry of the glTF model, such as author(s), licensing, as well as the original persistent identifier on the platform.

A few open-source frameworks, such as ATON, are able to extract such data at runtime that can be exposed at presentation level. Specifically ATON introduced support in 2022 for both custom schema in the glTF “extras” attribute (thus showing embedded information in glTF models downloaded from SketchFab for instance) and *KHR_xmp_json-ld* as well. In order to facilitate content creators and publishers in such a process, ATON also offers asset injectors operating on JSON formats, such as glTF or Cesium 3D Tiles.

## 4.3. Beyond the valorisation and preservation of CH

Although the current workflow already involves extensive collaboration among experts from various disciplines and institutions, it is essential to focus on the sustainability and reusability of a project of this size. While the primary goal here is to enhance cultural heritage, there is nothing preventing a digital twin from being adapted for other purposes, becoming a valuable tool for comparative studies.

The sustainability of reusing the knowledge base created with the digital twin lies in its adaptability: the digital twin becomes a structured container where the various components are replaceable, interchangeable, and modifiable according to different objectives. This flexibility is achievable only if the workflow used is replicable and well-defined.

In the context of Spoke 4, a recent example of this adaptability involved using the first two rooms of the digital twin for both usability testing and psychological research. A team of psychologists, designers, and digital heritage experts collaborated to gather requirements to define features that capture user behaviour in 3D and VR environments; develop a prototype with these features for a psychological study on navigation styles and spatial orientation in museum or exhibition settings; test the prototype with psychologists acting as operators during lab sessions with real users (Fig. 17); and analyse results to enhance the prototype's usability and functionality for broader applications beyond the pilot phase (Massidda et al. 2024).

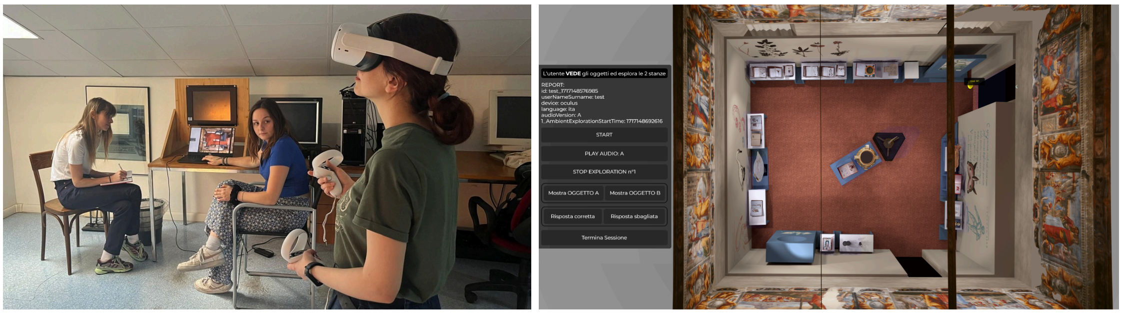


*Fig. 17: Observation of a subject conducting a VR session (left) and ATON virtual environment, with the admin panel (right).*

# 5. Conclusions

Our work described in this article has aimed to present a reproducible workflow for structuring acquisition and digitisation campaigns and digital twin creation in cultural heritage institutions (e.g. museums) and events (e.g. exhibitions). We have derived all the procedural steps of such a workflow from the work conducted on a pilot study, i.e. the temporary exhibition entitled *The Other Renaissance: Ulisse Aldrovandi and the Wonders of the World*, which ended in May 2023. In particular, we have detailed the material, methods, and tools we used (and, potentially, could use) for acquiring and digitising 3D cultural heritage artefacts, answering RQ1. Also, in light of the needs identified within the GLAM context regarding the acquisition and digitisation processes, we discussed possible practices and adoptions we have envisioned to improve and enhance the workflow's openness, accessibility, transparency, reproducibility, reusability and sustainability, thus answering to RQ2.

On the one hand, one of the main goals of this activity was to establish a shared and reproducible process for all acquisition and digitisation campaigns conducted in the context of Project CHANGES - Spoke 4, involving nine case studies developed within the project and implemented with the support of several companies funded by the project. These companies will work with heterogeneous cultural institutions that include natural history and scientific museums, widespread art galleries, site museums with (in)tangible heritage and landscapes, historical palaces, demo-ethnic anthropological museums, and museums with extensive collections and high-tech approaches. In particular, we are collaborating with institutions across the entire country: Museo Egizio in Turin, several museum networks in Italian universities (University of Bologna, University of Ferrara, University of Turin), Centro Studi e Archivio della Comunicazione (CSAC) in Parma, Ente morale Istituto Suor Orsola Benincasa in Naples, Carlo Levi and Grazia Deledda Literary Parks in Aliano and Galtellì, and Reggia di Caserta in Caserta.

On the other hand, another complementary goal of the work presented in this paper was to foster a culture of accountability and reproducible research by documenting a time-consuming and specialised research workflow in the area of cultural heritage. Indeed, adopting principles like FAIR and guidelines for documenting research methodologies in the humanities is a positive step and may become the norm in the academic setting. Several institutions and projects have proposed guidelines to make such processes as reproducible as possible, e.g. as detailed in the outcomes of the Horizon 2020 project 4CH (https://www.4ch-project.eu/). In the Italian context, the Italian Ministry of Culture (MiC) has recently established several guidelines (https://digitallibrary.cultura.gov.it/linee-guida/) in the context of the National Plan for Digitisation of Cultural Heritage, including those dedicated to the acquisition and digitisation processes. The reproducible workflow presented in this article aligns with MiC's guidelines by simplifying certain aspects, as our workflow is intended for valorisation and dissemination purposes rather than for documentation objectives, as in the case of the MiC.

As anticipated above, in the future, we aim to gather additional feedback from the adopters of this reproducible workflow within the nine Spoke 4 case studies. In particular, we want to analyse how such a workflow will be perceived by a series of different users, which include companies running acquisition and digitisation campaigns, the museum's curators involved and the other Spoke 4's partners managing the implementation of the case studies. In addition, we aim to add this workflow to the Social Sciences and Humanities Open Marketplace (https://marketplace.sshopencloud.eu/), built as part of the Social Sciences and Humanities Open Cloud project, which is a discovery portal for Social Sciences and Humanities research communities.

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# CRediT authorship contribution statement

Authors' contribution according to CRediT (https://credit.niso.org/):
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**Alice Bordignon:** Methodology, Visualization, Writing – original draft, Writing – review & editing
**Federica Collina:** Methodology, Writing – original draft, Writing – review & editing
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**Giulia Renda:** Methodology, Software, Writing – original draft, Writing – review & editing
**Mattia Sullini**: Methodology, Writing – original draft, Writing – review & editing

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