Shaping the World of 3D

Towards a roadmap for increased reusability of 3D cultural heritage datasets

Report of the 'Shaping the World of 3D' workshop at DANS, The Hague, 29 June 2023.

Final version, issue date 22 February 2024.

Grant Agreement number:	101004468
Project acronym:	4CH
Project title:	Competence Centre for the Conservation of Cultural Heritage
Funding Scheme:	H2020
Project coordinator:	Francesco Taccetti, INFN
E-mail:	francesco.taccetti@fi.infn.it
Project website address:	www.4ch-project.eu

Title:	Shaping the World of 3D: Towards a roadmap for increased reusability of 3D cultural heritage datasets
Issue date:	22 February 2024
Produced by:	DANS-KNAW
Main author:	**Pascal Flohr** (DANS-KNAW), ORCID 0000-0003-3203-913X – main and corresponding author: conception of the work, analysis and interpretation, drafting and editing of the text, addressing of reviewer comments.
Co-authors:	**René van Horik** (DANS-KNAW), ORCID 0000-0001-6899-760X – conception of the work, contributing to the text, presenter at the workshop. **Costas Papadopoulos** (Maastricht University), ORCID 0000-0003-1072-5198 – contributing to and reviewing of the text, presenter at the workshop. **Maurice de Kleijn** (eScience Center), ORCID 0000-0003-2379-191X – reviewing and editing of the text, contribution of presentation summary, presenter at the workshop. **Daniel Turner** (DANS-KNAW), ORCID 0000-0003-2216-8181 – reviewing of the text, presenter at the workshop. **Valentijn Gilissen** (DANS), ORCID 0000-0003-2399-7598 – reviewing of the text, presenter at the workshop. **Chiara Piccoli** (University of Amsterdam), ORCID 0000-0001-9854-4273 – reviewing of the text, presenter at the workshop. **Kate Fernie** (CARARE), ORCID 0000-0003-3733-0727 – reviewing of the presentation summary, presenter at the workshop (with Henk Alkemade, CARARE).
Version:	1.3, 8 February 2024
Reviewed by:	Hella Hollander (DANS-KNAW), ORCID 0000-0002-4079-7451 Tristan van Leeuwen (CWI), ORCID 0000-0002-8794-6426
Approved by:	Francesco Taccetti, 12 February 2024
Dissemination:	Zenodo, https://doi.org/10.5281/zenodo.10200379

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4CH is a Horizon 2020 project funded by the European Commission under Grant Agreement n.101004468 – 4CH.

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Abstract

On 29 June 2023, DANS organised the workshop 'Shaping the World of 3D' to bring together the community of those working with 3D research data in cultural heritage and/or archaeology in the Netherlands and Flanders. The aim was to establish a roadmap for best practices for management of 3D datasets in these fields to ensure their reuse and long-term preservation. This document summarises the presentations and discussions and presents a preliminary roadmap. The content varies from, for example, the strong recommendation for an internationally accepted common metadata standard to more practical recommendations for preferred file formats. We hope that the workshop and this resulting report can form a basis for a Community of Practice to further refine, but especially to realise, the identified tasks.

1. Introduction

1.1 Workshop rationale

An important aspect of archaeological and cultural heritage research is to document structures, features, landscapes, and objects. This can either be as part of excavation processes, landscape analyses, or as a basis for building historical or object analyses which are performed before renovation or reconstruction activities. Inherent to cultural heritage and archaeological research is that the object of study is subject to change as a result of both natural and human processes. To analyse the process of change, documentation is essential.

Since the emergence of 3D capture, visualisation, and analysis methods and technologies, archaeology and cultural heritage researchers have produced a large corpus of 3D datasets, especially over the last two decades. These can be virtual representations of real-life, still existing structures that are reality-captured in 3D, representations of features that are not existing anymore like phases in archaeological excavations and situations before the restauration of an object or the renovation of a structure, or virtual reconstructions with hypothesized representations of the past. This research is of high importance, and it is imperative to establish standards and systems to manage, preserve, and share the results properly. Questions remain about best practices regarding aspects of the datasets, such as long-term data storage, file formats, metadata standards and usage licences - all of which are considerations to facilitate reuse of such datasets in the future. Since the infrastructures for the management and reuse of 3D datasets are evolving both at national and European level, the workshop aimed at contributing a roadmap to inform the development and further improvements of these infrastructures. The planned workshop outcome was a roadmap for (best practices of) management and robust long-term access to 3D datasets.

1.2 Data management of 3D datasets

3D datasets consist of the files that form a 3D model, plus relevant metadata and other information for example in a README file. 3D models are always simplifications of reality, and there are two main types of model generation: reality capture (either of the surface or volumetric) and manual modelling (virtual reconstruction) (Moore et al. 2022). The types of date can be categorised as follows (see Moore et al. 2022):

- 3D point or mesh data, with different subtypes:
    - Captured by using photogrammetry, in which the 3D model is extracted from 2D images (photos). This results in surface meshes, which can be enhanced with colour and texture. The quality of the model depends on the algorithm and the camera sensor used.
    - Captured using aerial or terrestrial laser scanning or LiDAR, so that the 3D model consists of actually measured points (an x, y, z point cloud). This point cloud can be enhanced with colour and surface, usually from photos taken at the same moment.

  - Subsequently, the points are interpolated into a 3D model. So, the dataset consists of the measurements and photos (with the quality depending on the sensor), and the interpolated surfaces (with the quality depending on the algorithm).
  - Manual modelling, either source-based (based on documents, photographs, and other sources of information) and/or creative modelling. These are often done as 3D vector geometries and can be added to a reality-captured model or be stand-alone.
- Volumetric data, like the result of CT scanning or voxel art.
- Multimodal (mixed) data.

For data management, especially for long-term storage and reuse, an important distinction is between the raw data that comes from the sensors (photographs and measured points or point clouds) and the processed data (photogrammetry algorithm, etc.). A 3D dataset therefore contains multiple files and data structures, and some data formats in themselves contain multiple files.

The importance of good research data management is now generally accepted, and researchers are expected to deliver not only publications but also to preserve and make their data available for reuse. Although not yet sufficient, funding and support for this has become increasingly available. Many general aspects of research data management are applicable for 3D data and are not under discussion. For this we refer to useful guides like “Essentials for Data Support” (RDNL n.d.) and the “Data Management Expert Guide” (CESSDA Training Team 2017-2022). There are nonetheless several aspects that are different and/or not yet resolved for 3D data management, especially in relation to its preservation and reuse, such as the lack of one accepted international metadata standard for 3D data and infrastructural challenges for short-term and long-term storage (see Moore et al. 2022).

It is widely accepted that rich, standardised, and readily available metadata are key to the Findability, Accessibility, Interoperability, and Reusability (FAIRness) of data (Wilkinson et al. 2016). However, there is not one accepted international standard for 3D metadata. As a result, metadata (and paradata), essential for the reuse of a dataset, are not available, while the use of different standards, ontologies, and vocabularies leads to a diverse and not very interoperable collection of datasets. Efforts to describe the necessary metadata and paradata for 3D data in cultural heritage and archaeology for each of the different research or project phases (Fig. 1) have been going on for at least two decades now and have recently led to useful overviews of required and recommended metadata for 3D datasets (Medici and Fernie 2022; Moore et al. 2022; Smithsonian DPO 2018). The challenge remains to get these integrated and accepted widely. In addition, infrastructural challenges remain as to *how* and *where* to document and publish the metadata (see further below). Our objectives in this workshop regarding metadata were to find out which metadata, metadata standards, and (metadata) ontologies and controlled vocabularies are used by (the Dutch) cultural heritage and archaeology 3D community, how they are captured, and how (and if) they are made available.

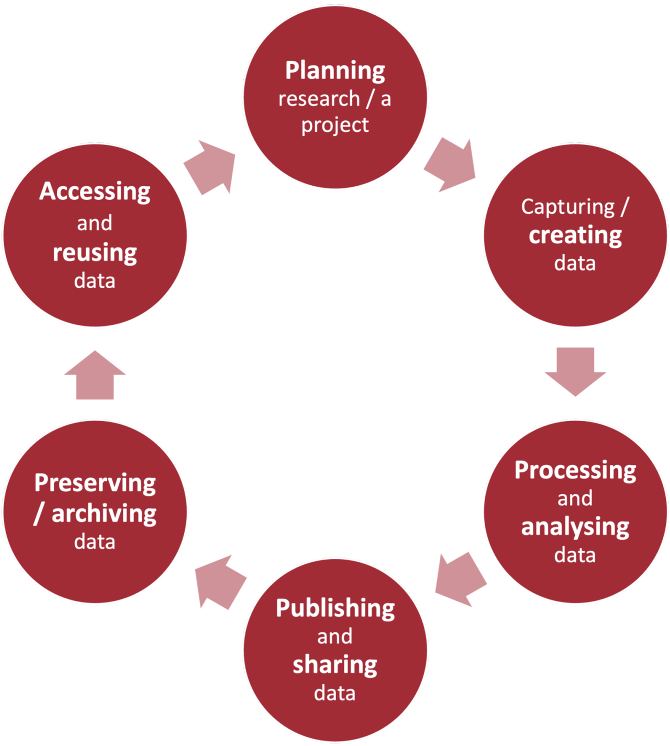

Figure 1. Research data life cycle (based on UKDS Data life cycle and 4CH D4.1 (Medici and Fernie 2022) digital asset life stages, although the latter has five stages in a somewhat different order: create, manage, distribute, and publish, access and reuse, archive).

Infrastructural challenges are also present for the access, storage, and preservation of 3D datasets. Such datasets consist of not only the extracted or interpolated model, but of multiple other files (depending on the type of 3D data, for example image files). In addition, and as a result, the datasets are relatively large. While the encountered sizes are not uncommon in the natural and life sciences, a 3D dataset is often much larger than the average dataset in the humanities and social sciences. This makes it more costly to store them, although storage costs are rapidly decreasing. Archives and repositories specialising in these disciplines are currently developing policies to manage 3D datasets. In the short term, organisations like universities generally offer server and/or cloud storage even for large volumes of data, and it is also common practice for researchers to keep a backup on hard drives. For long-term storage, however, it is important to clarify which parts of the dataset need to be kept for reuse: for example, it is not sufficient to only keep an exported file from proprietary software that was used to develop the final model, but also the original, raw data. It is also key to find the right balance between visibility (e.g. using a commercial platform like Sketchfab), findability (e.g. ensuring metadata are part of an aggregator like Europeana), and long-term preservation (e.g. using a Trusted repository like DANS). At a minimum, clearly indicated, and ideally open, licensing is also important. Key here are also data (file) formats suitable for preservation. Ideally, preservation file formats are commonly used, have open specifications, and are independent of specific software, developers, or vendors (Gilissen 2023). What is less clear, and something we were interested to hear from the community present at the workshop, is whether such an option is available for all relevant 3D recording techniques. Overall, our objectives were to identify what sort of software, file formats, as well as storage and sharing infrastructure are in use in the community.

Existing efforts on these topics include most notably the outcomes of the CS3DP project (Moore et al. 2022), aimed primarily at a US audience, the Smithsonian Metadata Model also included in Moore et al. (Smithsonian DPO 2018), the Share3D project outcomes (Share3D 2020), and the work done previously in the 4CH project (Medici and Fernie 2022). Useful information also comes from a survey on 3D infrastructures conducted by the PURE3D project (Schoueri et al. 2021) and a technical report on these by the same project (Fung et al. 2021). The current work builds on these very useful efforts. The CS3DP project identified five main themes, which we have integrated below: overall preservation best practices, metadata creation, access concerns, management and storage, rights, and ownership.

1.3 Workshop methodology

As mentioned above, the planned workshop outcome was a roadmap for (best practices of) management and robust long-term access to 3D datasets. To get here, the workshop started by identifying what is commonly being done regarding the management of 3D research data and to subsequently explore what is still needed or required to improve the current state. This could eventually lead to a best-practice scenario. To achieve this, the next step was to gather solutions and ideas, and finally to identify practically what steps could be taken and by whom. Specifically, the questions asked during the workshop were:

- What is the state-of-the-art?
  - Which formats, storage solutions, other infrastructure, etc. are currently being developed and used?
  - How are 3D data being (re)used in current archaeological and cultural heritage research?
- What is needed / required?
  - What are the requirements for the reuse of 3D data (in archaeology and cultural heritage)?
  - Is anything missing? What is needed to get to a ‘best-practice’ scenario?
- What are our ideas or solutions for the future?
- Who should / can do what? How could the work, responsibilities, and costs be divided?
  - How do we practically work towards a best-practice scenario?
  - How can we coordinate the work?

2. Summary of the workshop

2.1 Audience and interest

The workshop took place in The Hague on the 29th of June 2023 and was attended by 25 people from various universities and cultural heritage organisations from the Netherlands and Flanders. The (invited) speakers are actively involved with 3D data in cultural heritage and/or archaeology and are linked to projects like 4CH and PURE3D, research groups like the 4D Research Lab, and/or organisations like CARARE, the RCE, the eScience Center, Visual Dimension, Europeana, and DANS (appendix I and II). The remaining audience consisted in large part of university- or research-institute-based researchers and (to a lesser extent) of students, ranging from beginners with an interest in developing and (re)using 3D data to researchers experienced in using it. The companies Conzept and Design Party Program were also represented. Participants' link to 3D data varied from archaeologists using it for documentation purposes to people with a full focus on 3D applications in cultural heritage.

There was considerable interest in attending the workshop remotely; the choice was specifically to have an in-person meeting to facilitate informative discussions, but this shows that there clearly is an interest in the topic.

2.2 Presentations

The presentations and short discussions that took place as part of the workshop, covered three topics: 3D applications in research, with a focus on (requirements for) reuse; data management of 3D data; and coordination initiatives like Europeana and 4CH.

2.2.1 Examples of 3D applications

Three examples of 3D applications were presented in the first part of the workshop. These provided an insight into how 3D technologies can be applied in archaeological and cultural heritage research, with a specific focus on reuse.

The PURE3D project, presented by Costas Papadopoulos and Susan Schreibman, is developing a national infrastructure (funded by PDI-SSH) for the publication and preservation of 3D scholarship: both an access infrastructure for viewing interactive 3D models within the context of a scholarly publication format and a preservation repository for 3D models and files. The project also aims to provide a conceptual and methodological framework for valorising, evaluating, and publishing interactive 3D scholarship. Several pilot projects have been initiated to showcase how 3D models can be turned into '3D Scholarly Editions'; a format that allows the presentation of 3D models accompanied by rich contextual and multimodal narratives. The open-source online 3D viewer Smithsonian Voyager forms an essential component of the infrastructure (Smithsonian DPO n.d.). Upon the completion of the infrastructure, users of PURE3D will be able to search and browse 3D content, as well as to author and publish 3D scholarly editions (through an administrative interface using the CLARIAH authentication). The Smithsonian Voyager Explorer, and potentially other viewers, make it possible to view the 3D data. A repository with narrative annotations and metadata underlies this. The presentation also raised important questions regarding reuse of 3D data, like how do we make 3D FAIR, how do we deal with versioning, and how do we deal with the absence of modelling and digitisation standards, also in relation to the impact of the resulting variation on infrastructures?

Daniel Pletinckx of Visual Dimension explained the process of virtual reconstruction of sites and buildings (/objects). He stressed the importance of the use of multiple, multidisciplinary sources, going beyond just historical records and physical or archaeological remains. The example of 17th century Fort Lillo showed how sight lines and engineering knowledge give valuable additional insights (see University of Antwerp n.d.). The main problem, however, is how to preserve a work like this. During the questions, the importance of documenting this process was highlighted: how was the knowledge transformed into the 3D models?

The 4D Research Lab was represented by Chiara Piccoli, who talked about experiences with reusing 3D models. In the Virtual Interiors project, she worked on the reconstruction of a selection of 17th century houses in Amsterdam, using written sources to determine what the rooms may have looked like and what they may have contained (see Appendix II for links). For a few objects in one room (e.g. a 17th century globe), she searched for CC (open) licensed items available through Sketchfab, to reuse these rather than redo the same work. For the virtual reconstruction of the Jewish Quarter in Amsterdam she is also aiming to reuse parts of the models that were previously made by the 4D Research Lab for the Vlooienburg project. What is interesting here is also that her methodology uses procedural modelling, generating the 3D model based on a set of rules instead of manual modelling. She combines GIS for the mapping of data with CityEngine, in which it is, for example, possible to place comments in the script on which modelling decisions were made and on the provenance of the used items. Chiara clearly stressed the importance of 3D data provenance and of preparing 3D models in a way that facilitates their potential reuse, ideally working with / setting up libraries of trustworthy individual 3D models (items) to mix them to recreate a new scene.

2.2.2 Data management of 3D datasets

The second topic of the workshop emphasised the management of 3D assets.

Daniel Turner and Valentijn Gilissen of DANS presented a 3D data management case study, where Valentijn in his role as senior data manager at DANS helped Daniel with the long-term preservation of his 3D photogrammetric research data in the DANS Data Station Archaeology. These data were created as part of the SETinSTONE research project (Brysbaert et al. n.d.). For Daniel's role within this project alone roughly half a terabyte of data was created, even though most of the models were simple mesh and point clouds without texturing. The challenges were therefore the required storage space and the RAM required during processing, as well as the fact that proprietary software was used. An added difficulty was that already after a couple of years it proved challenging to retrieve the original data from the external hard drive or laptop where they had been stored, showing how important it is to store your data in a trustworthy digital repository during the lifetime of a project. Valentijn's team used a 30-day trial version of the proprietary software Agisoft Metashape Professional to convert the proprietary file formats (.psz/.psx) into open ones (only binary .ply was supported), so that reuse and future curation are more straightforward. As a repository, one of the roles of DANS is to advise on preferred file formats, and to curate datasets. Advice is also given on metadata for the datasets. Regarding the larger storage requirements than usual, at least for DANS, tape storage was mentioned as a possible solution, in combination with only storing what is necessary for reuse. Detailing DANS' guidelines and strategies for the long-term preservation and accessibility of file formats, Valentijn asked the audience for user input on the DANS preferred format guide: if, looking from a user perspective, the guidelines were lacking details on certain formats or if anyone had any comments on the existing guidelines. Several additional formats were indicated as being used by members of the community. Valentijn has since looked at these formats and is in the process of including recommendations on them in the DANS guidelines.

The Mapping the Via Appia project was presented by Maurice de Kleijn of the eScience Center. In this ambitious project more than 2,000 objects of the road and six funerary monuments were modelled in a point cloud, with the underlying data derived from LIDAR scans, pictures, excavations, photogrammetry models and DGPS measurements. The results have been made available through an online viewer (https://via-appia.netlify.app/). Importantly, the decisions made throughout the process of creating the 3D model were mapped, making it possible for others to question (and reuse) the underlying research and decisions made (De Hond in prep.). The project would ideally like to store all models with an annotation for everything, but the software to do this currently does not exist, so the information is now stored separately, while this software is being developed by the eScience Center. The main other issue raised was the need for a standard data model.

The presentation by Kate Fernie and Henk Alkemade of CARARE was an extremely useful overview of the main challenges in the management of 3D cultural heritage data and how to do this in a FAIR way. The points and solutions raised in this presentation have been integrated in section 3 below, but briefly summarising: The main challenges are the different sizes, scales, and large variety in cultural heritage, with varied use cases and objectives. In terms of FAIR data management, to make datasets findable, they should have high-quality metadata and persistent and unique identifiers. To make datasets accessible, they should be stored in a trustworthy repository with retrieval protocols and standards. To make datasets interoperable, metadata are key, with information on the project, cultural heritage, and digital data, using existing metadata schemas like CIDOC CRMdig, LIDO, CARARE, Smithsonian, and controlled vocabularies (ideally Linked Open Data, like through using the Getty's Art and Architecture Thesaurus). For reusability of both content and metadata a suitable licence is key, with open licences preferred if possible. The Share3D platform (https://share3d.eu/) was highlighted as a way to capture metadata from Sketchfab, improve it, and migrate the metadata to Europeana. In the subsequent discussion about the use of Sketchfab, it was concluded that this commercial platform can be used for making a model visible but should not be used for storing a model.

The interactive session by Bart Boskaljon (RCE) and Sanne Frequin (Utrecht University) also focused on the preservation of 3D data, using the example of the 3D model of the tomb of Guy de Avesnes, present in the Utrecht Dom church (see also Redactie Geschiedenis Magazine 2022). The model was made by Sanne Frequin and was initially only preserved on a hard drive. The group was invited to define the problems around the preservation of such a model: how can the model remain accessible for 50 years? Various issues were raised, such as that output like this is not valued and therefore no time is (can be) allocated by researchers to submit this to institutional or external repositories. You also need to know what it is that you need to preserve, and importantly who will do the preserving - curation like the migration to new file formats will be needed.

2.2.3 Coordination activities

The third topic of the workshop focused on organisational aspects in relation to the management of 3D datasets.

Valentine Charles introduced the latest on Europeana and the European Data Space for Cultural Heritage (Europeana Foundation 2022). Europeana provides access to digitised European cultural heritage collections, and 3D data is gaining importance in this respect. Europeana is involved in the European Data Space for Cultural Heritage, one of the fourteen Data Spaces currently being developed by Digital Europe. The aim is to provide a platform for decentralised data sharing, so that institutions can retain control of their data, yet share them. The presentation also covered other initiatives Europeana is involved in, such as TwinIT, a campaign on behalf of the European Commission to 3D-digitise monuments and sites at risk, at the same time creating momentum for this at a national level (Europeana Foundation n.d.). Valentine pointed out that it is important to take into account the different requirements per use case or purpose when defining what good-quality 3D data means. It is, for example, not necessary to have a highly detailed model just to visualise something to a school class.

Finally, René van Horik of DANS introduced data management within the 4CH project, the reason for organising this workshop. The 4CH project aims to formulate recommendations and guidelines for the management of digitised cultural heritage assets. The preliminary list of recommendations was presented, including differentiating between user groups, aligning activities with (national) digitisation policies for cultural heritage, cooperating with and joining related initiatives, applying the FAIR principles, and creating a Digital Management Plan.

3. Outcomes

The discussion was structured around four questions concerning the management of 3D datasets:

- What is the state-of-the-art?
- What is needed / required?
- What are ideas / solutions for the future?
- Who should / can do what?

Input on these topics was also collected during the day: during the presentations and from questions afterwards and (short) discussions in between. During the longer discussion in the afternoon, the participants were divided into four groups to facilitate discussion, with a note taker for each group. Below is a summary of the notes based on the presentations, notes about the questions and short discussions during the day, and notes made during the longer discussion session. There are also some additions made by the authors and contributors afterwards based on relevant literature and their own experience.

In general, to facilitate reuse, 3D data should comply with the FAIR principles; one of the questions raised (and answered) during the presentations was how to do this. Data can be made findable through the use of metadata and persistent identifiers; made accessible through storage (preservation in an archive) and standards; made interoperable through the use of ontologies, controlled vocabularies, and linked open data; and made reusable through giving people access and making clear how it can be used (licence, standardised rights statement) (Fernie and Alkemade this workshop).
Therefore, this section is organised by the following main themes:

- Standards
- Metadata
- File formats
- Infrastructure: Storage (long-term)
- Infrastructure: Other
- Software
- Governance & coordination

The theme of interoperability and ontologies or vocabularies was recognised but due to time constraints not extensively discussed.

3.1 Standards

What is the state-of-the-art?

- There is currently an observable absence of internationally recognised modelling and digitisation standards for 3D data. The resulting variation has an impact on interoperability and may also have an impact on the infrastructure (e.g. 3D models potentially cannot be ingested because of this).

- Available standards / guidelines:
  - London Charter for Computer-based Visualization of Cultural Heritage (2009) (https://londoncharter.org/).
  - The Seville Principles (López-Menchero 2013; López-Menchero and Grande 2018).
  - Extended matrix (Demetrescu 2015).
  - Medici and Fernie 2022.
  - CARARE metadata schema (see also below under metadata) (CARARE n.d.). The 3D-ICONS schema is based on this (3D-ICONS n.d.).
  - Industry standards, e.g. for CAD, Engineering Drawings, imaging systems, BIM, industry standard file formats.
  - Best practice documents, e.g. ADS guide on 3D models in archaeology (Trognitz and Gilissen 2016).
  - Smithsonian 3D Metadata Model (Smithsonian DPO 2018).

What is needed / required? (i.e. what is missing?)

- Commonly agreed-on standards / standard data model: metadata, modelling, and digitisation standards.

What are ideas / solutions / recommendations for the future?

- Remark: the International Image Interoperability framework (IIIF, https://iiif.io/) gains importance when it comes to managing images, including 3D data. The IIIF stands for a set of open standards for high-quality, online, "attributed digital objects", as well as for the community developing and implementing the framework's APIs.
- For reuse, metadata standards are key.

Who should / can do what?

- For commonly agreed-on standards, these should be agreed on by the 'community' (for example through a community of practice), consisting at least of cultural heritage / archaeology 3D experts as well as data experts (e.g. data management experts, data/computer scientists).

3.2 Metadata

What is the state-of-the-art?

- Metadata (and paradata) are absolutely key for findability, interoperability, preservation, and reuse. Types of required metadata are comprehensively summarised by Medici and Fernie 2022 and Moore et al. 2022.
- Currently, many 3D projects are not capturing (and/or publishing) enough metadata for reuse (especially for research reuse), sometimes not even enough for findability or

discovery. Or the projects are capturing the metadata, but it is not possible (lack of infrastructure) to connect these clearly to the data.
- While there is currently not one single, international standard, various metadata schemas are currently in use, for example:
    - CIDOC CRMdig. For provenance of digital objects.
    - LIDO. For museums, museum objects.
    - CARARE and related schemas like Europeana - Share3D. For monuments, buildings, landscape areas.
    - Smithsonian 3D metadata model. Focused on museum 3D programmes.

These and other metadata schemas are discussed in more detail in Medici and Fernie 2022 and Flohr et al. forthcoming.

What is needed / required? (i.e. what is missing?)
- The main important thing identified is to establish 3D (data) standards / a standard data model. Interoperability is currently challenging.

What are ideas / solutions / recommendations for the future?
- Metadata that should be collected:
    - Title (e.g. Dublin Core title)
    - Provenance: who made it (creator), from which sources, which context, how did you get to the model, how were missing data recovered.
        - E.g. PURE3D and DANS 3D metadata include DublinCore creator and DC contributor.
        - E.g. the Via Appia project includes mapping of decisions so that others can question (and reuse) the underlying research and decisions (De Hond in prep.).
    - Project information: scope, goals, date, methods, techniques.
        - E.g. PURE3D and DANS 3D metadata include Dublin Core identifier for Project ID.
    - Cultural heritage information: the object that has been captured, subjects/themes.
    - Digital data: how was the data produced, model information, access & licence, version.
- Aim for the best, but also accept the good.
- Metadata should be openly available.
- Use existing schemas like CIDOC CRMdig, LIDO, CARARE, Smithsonian.[1]
- Move towards one internationally accepted metadata standard for 3D data.
    - CIDOC CRMdig as high-level ontology (exists in RDF), but further levels needed to be complete.

[1] See Medici and Fernie 2022 for recommended metadata schemas for cultural heritage.

- Recommended to at least use controlled vocabularies and word lists (e.g. Geonames for place names), but best to use Linked Open Data like the Getty's Art and Architecture Thesaurus (AAT).
- How to document metadata?
    - Metadata inside the file with for example glTF or Draco. You can then also link, with 3D becoming web native.
        - Promising AI solutions to automatically generate detailed metadata.
    - The City Engine script allows placing comments on modelling decisions, such as provenance (currently used by the 4D Research Lab; City Engine is proprietary though).

Who should / can do what?
Not specifically discussed.

3.3 File formats

What is the state-of-the-art?

- Currently, the used file format depends on the preference of the user, some use proprietary formats (e.g. .psx, .psz) while others use open source formats.
    - Quite a wide range of formats are in use, see for example the Nieuwe Instituut archive (https://zoeken.hetnieuweinstituut.nl/en/).
- Preferred format lists, such as compiled by DANS (Gilissen 2023) and ADS (Trognitz and Gilissen 2016), include 3D data formats.[2] Generally recommended are ASCII-based files for point coordinates and commonly used, ideally open file formats.
- Formats like Autodesk FBX (.fbx), Blender (.blend), or 3D PDF (.pdf) are generally considered non-preferred.
- glTF or Draco: metadata are inside the file. These formats exist but are not commonly used yet. Can be queried with SPARQL language, can also be linked, 3D becoming web-native. They have been designed to have a small file size.
    - glTF (.gltf): GL Transmission Format. Stores 3D model information in JSON (Khronos Group - glTF Github 2023; Khronos Group webpage n.d.; Fileformat - GLTF n.d.; Wikipedia - glTF n.d.). It represents 3D models through full scene description contained in a JSON-formatted .glTF file that includes information about node hierarchy, materials, cameras, descriptor information for meshes, animations, and more; binary .bin files with geometry data, animation data, other buffer-based data; image files .jpg, .png for textures. Its developer calls it the "JPEG of 3D" (Khronos Group webpage n.d.). It can be used without fees or royalties (but it is not completely open).

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[2] The UKDS recommended and other acceptable formats list does not include 3D formats (https://ukdataservice.ac.uk/learning-hub/research-data-management/format-your-data/recommended-formats/).

- Draco (.drc): compressed 3D file format created with the open-source Google Draco library. The input data are encoded and saved as a .drc file, and the API can read .drc files and output them as .ply or .obj files (Google - Draco GitHub n.d.; Fileformat - DRC n.d.).

Table 1: Preferred and recommended file formats for 3D data. The ADS list was published in 2016 while the DANS list was updated in 2023, so that for new projects the DANS list and recommendations from the workshop are better followed than the ADS list.

Format	**Extension**	**Included on preferred format list / source**	**Remarks**
WaveFront Object	.obj	DANS	ADS (2016): for wireframed or textured models
Polygon file format	.ply	DANS	ADS (2016): ASCII version suitable if file content is clearly documented
X3D	.x3d	DANS, ADS	ADS (2016): recommended for complex 3D content
COLLADA	.dae	DANS	ADS (2016): recommended where X3D is not an option
Standard Tesselation Language	.stl	ADS	ADS (2016): ASCII format suitable for very basic datasets
Virtual Reality Modelling Language	.wrl, .vrml, .wrz	ADS	ADS (2016): “now” replaced by X3D
Autodesk Drawing Interchange Format	.dxf	ADS	ADS (2016): only suitable for preservation of native CAD datasets
glTF	.gltf, .glb	Recommended during this workshop	
Draco	.drc	Recommended during this workshop	
LASer	.laz / .las	Recommended during this workshop	Point clouds. The format comes from LiDAR but can also be the result of photogrammetry processes.

What is needed / required?

- (increased use of) interoperable formats
- Community feedback on formats.
    - E.g. feedback in the workshop was to add glTF, Draco, .laz/.las to the list of preferred 3D data formats. glTF is already recommended by CARARE, but are .laz/.las and Draco also widely used/supported or could they be in future?
- Straightforward conversion.

What are ideas / solutions / recommendations for the future?

- The recommendation for the ideal format should remain: frequently used, with open specifications, and independent of specific software, developers, or vendors.
- But realise that this is not always possible in practice: repositories should be flexible and accept non-preferred formats as well, since storage/publication of a non-preferred format is better than no storage/publication at all. But make sure, when possible, to migrate files to preferred formats, like ASCII-based point clouds.
- To add .laz/.las, .gltf, and possibly .drc to preferred formats lists.
- Use of smaller formats, like glTF or Draco.
- Further development / increased use of 3D formats that include semantic annotations, which could be aggregated into an RDF triplestore so it can be accessed by SPARQL queries (related examples: CityGML, IIIF 3D).
- Important to select robust formats for the original data. The DANS example (see section 2) shows that options to change the file format during curation may be limited. In this case study the original model was produced in the proprietary software Agisoft Metashape Professional as .psz/.psx files and a trial version of the software was used to export to an open format, but the only option for the latter was binary .ply.

Who should / can do what?

No notes from the workshop itself on this, but we suggest:

- 3D researchers and practitioners to indicate which formats work for them, and why.
- Also testing formats which are new to them, but which are recommended above.
- Developers/repositories to recommend open-source formats, if necessary to develop new formats.
- Research supporters (including at repositories like DANS) to provide guidelines on how to use certain formats, recommendations on which formats to use (reiterative with the two points above).
- Repositories to keep up to date with the latest developments and curate stored files to preferred formats.

Other comments

File formats are not the most difficult issue for preservation and reuse of 3D data.

3.4 Software

What is the state-of-the-art?

- Currently both open and proprietary software are used.

Table 2: Software for 3D data processing and modelling as mentioned in the workshop (so this is an not exhaustive list of all available software, it would be good to produce such a list, see also the roadmap).

Name	Access	Function
Blender	Free and open source	For hand-made modelling
Meshroom	Free and open source	For image-based modelling
Meshlab	Free and open source	For 3D processing and editing
Esri City Engine	Proprietary	For rule-based modelling, allows for placing comments on modelling decisions (i.e. metadata)
AutoCAD	Proprietary	For digitising plans
QGIS	Free and open source	Geographic Information System software, not specifically for 3D modelling but can be used to place existing 3D models in a 3D scene, create 3D maps. There is a 3D plugin which allows some modelling.
Potree	Free and open source	For viewing / rendering point-clouds
3Djs	Free and open source	For data visualisation
Cloud Compare	Free and open source	For processing point clouds and triangular mesh
PostGIS	Free and open source	For supporting databases in storing and querying spatial data
Agisoft Metashape Professional	Proprietary	For photogrammetry

- As with other types of data, there are clear disadvantages to using proprietary software (e.g. as shown in the case study presented by Daniel Turner and Valentijn Gilissen of DANS, where files could only be opened again by getting a free trial / paying).

What is needed / required? (i.e. what is missing?)

- We need to find out if it is possible to do everything with open-source software to understand if anything is missing.
  - E.g. is there software that can do rule-based modelling with annotated metadata in the model, as Esri City Engine does? Could one digitise plans using QGIS?
  - Open data formats are more relevant during the preservation and reuse stages than during the processing stage, so if files of models produced with proprietary software can be exported to open and interoperable formats for long-term preservation and reuse that is fine.

What are ideas / solutions / recommendations for the future?

- Development of the required software, for example as plugins for Blender, QGIS, and/or other existing software.

Who should / can do what?

- Software development: e-Science Center (idea: for example as part of a larger consortium to apply for funding).

3.5 Storage and storage infrastructure

What is the state-of-the-art?

- Typical storage sizes for one dataset: one model in one project was based on 12,223 photos, 19 clusters and 254 GB of data, for a simple mesh and point cloud (Daniel Turner).
- Existing storage solutions (long-term preservation):
  - Trusted (certified) repositories like DANS: curated, (can be) open, rich metadata.
  - Generic, international digital repositories like Zenodo: open, can have rich metadata, not curated.
  - Institutional repositories: depending on the institution, some have rich metadata and are open, generally files are not curated.
  - Bespoke solutions, but these tend to lack sustainability (e.g. funded for project duration only).
- Short-term storage (during active research phase):
  - SURFdrive (a cloud service for the Dutch education and research community) is used, as are hard drives and institutional storage (hard drives only undesirable though).
  - University servers (e.g. the Via Appia data is stored on the Radboud University server).

- The move from 'short-term' storage on university servers to long-term repository storage is often not (yet) made, also awaiting research publication.
- Sketchfab is often used, but not useful for storage or reuse, only for visibility. The Smithsonian 3D Voyager may be a better option, but it is not a repository in itself, but rather a suite of software tools: Explorer for viewing, Story for authoring, and Cook for processing (Smithsonian DPO n.d.). The PURE3D project is currently setting up this Smithsonian suite of tools at a server with an underlying repository.
- Share3D: tool to easily upload 3D models to Sketchfab and the metadata to Europeana (https://share3d.eu/).

What is needed / required? (i.e. what is missing?)

- A long-term sustainable approach.
- Infrastructure for larger sizes, for both storage and processing power (RAM). 3D dataset sizes are larger than we are used to in the humanities (or cultural heritage & archaeology).
    - Tape storage may be an option.
    - Maybe this is not a big issue: Data storage is getting cheaper and 3D datasets are not that big compared to datasets from other disciplines.
- Knowledge from the community on what we need to keep for reuse and what should be documented in the first place. Even if it would be possible to keep everything regarding dataset sizes, this is not desirable if it is not necessary: It is a huge operation to document, store, and curate everything (costly but also takes time).
- Infrastructural development of relevant (i.e. social sciences, humanities, archaeology) repositories, like the DANS Data Stations, so that larger file sizes can also be uploaded easily.
- An inventory of 3D datasets (see also above).

What are ideas / solutions / recommendations for the future?

- Learning from solutions in the natural sciences, where they deal with much larger file sizes (i.e. petabytes) and work with 3D data.
- Recommendation for long-term storage and preservation to store parts of the dataset required for reuse in a trustworthy repository where the datasets are curated, i.e. formats are migrated.
    - A repository without curation, e.g. university repository, is the next best approach.
    - But not just on a hard drive or Sketchfab. Sketchfab at some point was the best solution at least for sharing and viewing, but the data is difficult to reuse, it is commercial so there is no control over it; it is fine to use for making data more visible (although see below for further discussion on this) but not for storing.
    - Sustainable migration should be part of institutional plans in case of dissolution of the repository or even whole institution.
- Cascade system: what is needed for the objective, i.e. monument or site that is not under threat does not need a high-resolution scan or many photos (prioritisation based on risk, and objectives; for archaeology that is being destroyed high resolution scans/files are

needed and need to be kept with paradata and metadata). Focus on the **core** that needs to be kept in order to preserve and redo the model? E.g. in photogrammetry you could keep the photos but do not need to preserve the model, or only the simple model. Concept of most affordable 3D.
  - There was no general agreement on this, it was also pointed out that making and keeping high resolution scans of everything (and freely distributing them) may be better.
  - Who decides?
  - Original scans should be shared and stored.

Who should / can do what?
- Who is responsible for long-term curation?
- Who decides on what to keep?
- Who decides on and who controls access? E.g. for sensitive data, ethical issues (e.g. human remains even when archaeological).

3.6 Other infrastructure

Difference between findability and preservation aims (for preservation and storage, see above).

What is the state-of-the-art?
- 3D data made available through the web.
- Sketchfab, while not useful for storage and reuse, is useful for visibility. The Smithsonian 3D Voyager tools may be a better option, since Sketchfab is a commercial platform and long-term sustainability is unclear. It is for example unclear what will happen to the 3D models of cultural heritage in the longer term now the platform has been obtained by Epic Games and there is no longer a cultural heritage lead in the company.
- Share3D as mentioned above: tool for sharing models through Sketchfab and metadata through Europeana.

What is needed / required? (i.e. what is missing?)
- An inventory of 3D datasets that are out there and how they are currently stored, like data that is currently on hard drives, or organisational servers or cloud storage.
- A compendium, or metadata catalogue, an overview of what is where (not complex).
  - Currently students tend to go to Sketchfab and see it as the only source for 3D models.
  - A lot of heritage institutions do not know what they have in terms of 3D data.
  - Something like Share3D but not reliable on Sketchfab (Smithsonian Voyager useful?). Accessing 3D heritage via a URI and/or 3D viewer.
  - Authoritative libraries of individual 3D models to mix them and recreate a scene (with checked / trusted models).

What are ideas / solutions / recommendations for the future?

- Develop software for a smooth workspace that includes smooth archiving.
- Preserving interactivity of platforms that go out of use.
- Data should be independent of the viewer: preservation / storage / reuse is not the same as findability / discoverability. For 3D experts, the possibility to download data is much more important than being able to view the model online (see De Kleijn et al. 2014).

Who should / can do what?

- Software development: e-Science Center.

3.7 Coordination and governance

What is the state-of-the-art?

- One very relevant initiative is Europeana, currently working on the European data space for cultural heritage, previously set up Europeana.eu, where cultural heritage (meta)data is available for viewing, sharing, use, and reuse.
- The European data space for cultural heritage is being developed. Horizon Europe funding has been awarded for the Data Space and for smaller projects to develop related tools. As more calls will happen in the coming years, there is substantial investment in 3D infrastructures at the European level.
- Even though application of 3D technology is gaining ground, the knowledge and expertise is spread over many parties. Bringing this knowledge together and organising its dissemination should be part of the roadmap.

What is needed / required? (i.e. what is missing?)

- National and international cooperation and policies on multiple levels.
- Defining ownership and the extent of open access (e.g. digitising private residences).
- Someone from above to harmonise, determine which standards, ontologies, etc to use.
    - Bottom-up/distributed solutions such as Wikipedia vs top-down centralised actors such as the EU and related projects.
    - Community buy-in and community involvement are key.

What are ideas / solutions / recommendations for the future?

- Top-down and grassroots approaches: mandates from institutions/funders and adoption from users.
- Linking different organisations, people, with different standards / ontologies. Example of Rijkswaterstaat, based on the experiences De Kleijn had as project leader for integrating 3D data from various departments, and maintenance organisations: illustrates the need for common standards and practices (and how this can be achieved).
    - Technically using IIIF, gltF; but there is also the important human side, how do you get people to agree?

- From the CS3DP publication: a common vocabulary needed to be developed in order to go beyond just acknowledging issues of digital preservation. To move from "acknowledgement to action" (Moore et al. 2022: 5).
- To acquire funding to address the needs and requirements, a larger consortium to apply for an EU grant would be good to set up.

3.8 General needs and recommendations to improve 3D data reuse

- The level of data management, and decisions made, depend on the aim and objectives of the study or project. Research, educational, tourism, and creative industries all have different reuse requirements (e.g. reuse for research purposes requires very rich metadata and paradata).
    - Recommended: Medici and Fernie (2022) describe metadata and paradata required for each phase of a project.
    - Recommended (but still in press): Huvila et al. (eds). Perspectives on paradata: Research and practice of documenting process knowledge. Springer.
- Publish all and rich metadata, publish data as openly as possible.
    - Define a suitable licence, CC0 or other public domain is preferred.
- Need for a clear workflow: efficient, avoiding bureaucracy, access for experts.
- Clear guidance for researchers: what is needed for preservation, what are the best methods, etc.
    - Tied in with the clear workflow: when planning ahead good data management takes much less time.
- Concrete data management rules and regulations, required, and paid for, by funders.
- More support for researchers, who have little time to do in-depth data management as proposed in the workshop and this document (e.g. use of standards, preparing data for depositing, etc.).
- Training new generation of 3D researchers who follow more concrete workflows.
- Increase the value and recognition of publishing data, as well as awareness of its importance. Currently data are still not valued as much as publications as a research output.
- A long-term sustainable approach is key.
- Application of persistent and unique identifiers (PID) for data files, researchers, publications, and other objects.

4. Roadmap to improve the long-term access and reuse of 3D cultural heritage data assets

Based on the presentations and discussions during the workshop, we propose here a draft roadmap with the aim of improving long-term access and reuse of 3D datasets in cultural heritage and archaeology, with a focus on the Dutch landscape. While we hope that concrete actions will already be undertaken based on the identified tasks, the main idea is currently that this draft can be used as a basis for further discussions. Even when a more complete roadmap is defined, it will remain flexible, to be adjusted and updated. In its current form, the ‘who’ and ‘when’ columns are to a large extent empty, as this was not much discussed during the workshop. We have nonetheless added these columns, as the next step is to complete these.

No	Task / activity	Description / comments	Recommended type of organisation(s)	Priority / due date (TBA)
1	Bringing together knowledge and expertise on 3D data management.	Through a Community of Practice, focused on the Dutch (/European) landscape, like the CS3DP in the United States. To bring together the currently more disjointed efforts. Goals for this Community of Practice need to be specified, but should include engaging with international bodies to learn from previous work and broaden the scope. To include an online platform for sharing best practices.	Building on this workshop; (initial) organiser to be decided; all to participate	
2	Identify (map) existing 3D datasets in archaeology and cultural heritage domain (in the Netherlands and Flanders only or in general).	Identify what sort of 3D data is used in the cultural heritage and archaeological domain. What formats, software, metadata schemas, vocabularies, etc, are used, how are the data shared under which licence, and where are the data stored in the short- and long-term? The aim is to better understand needs, current gaps, and which solutions already exist. This could be	Building on this workshop, e.g. Community of Practice; at least in cooperation with / including the PURE3D project	

		done as a survey, e.g. through the Community of Practice, and join the inventory of 3D projects being done by the PURE3D project.		
3	Work towards an internationally accepted standard for 3D metadata / a standard data model.	Agreement on metadata, modelling, and digitisation standards. Through setting up / taking part in national and international cooperation. It is important that this is done at least at EU-level, in terms of facilitating interoperability and given the developments for the European Data Space for Cultural Heritage and the European Cultural Heritage Data Cloud.	To be defined. It was discussed in the workshop that top-down management is needed as well as community involvement and grassroots approaches.	
4	Integrate standard metadata fields into existing repositories, e.g. the DANS Data Station Archaeology and the DANS Data Station Social Sciences and Humanities.	To encourage the use of the metadata schema of Task 3, repositories should enable the addition of the 3D metadata. This should not only include the technical addition of these metadata elements, but also the provision of guidance, training, and support. The adoption of the metadata fields by depositors should subsequently be monitored and evaluated.	Repositories, e.g. DANS	
5	Create a metadata catalogue of 3D datasets (/ identify and use an existing catalogue and enter the found datasets there).	A place to find the datasets collected as part of the inventory (Task 2).	To be decided	
6a	Update the list of preferred file formats, make this more easily available, and raise awareness.	More suitable file formats were suggested in the workshop and more may come up during the inventorisation. This should be reflected in the recommendations done by repositories and research supporters.	Repositories and research supporters, e.g. DANS	

6b	Research and (possibly) encourage the use of interoperable file formats.	Better interoperable file formats were suggested during the workshop. This deserves further looking into. This can be done in line with EU standards that will be defined during the development of the European Cultural Heritage Cloud and Data Space.	To be decided	
7	Create/adopt a tool for easier conversion between formats	It is now not always easy to convert between the different formats, and such a tool could be helpful. Note, however, that this task is complicated, especially for 3D models created in 3D modelling software, since the textures, lights, materials, etc., are not always easily convertible to different formats.	To be decided	
8	Encourage the use of existing open software and/or develop open software where missing.	It is key to establish if open software exists that is sufficient for all the required tasks relating to 3D modelling. If there are tasks that cannot currently be conducted with open software, the recommendation would be to develop this.	E.g. eScience Center with larger consortium and/or through project calls	
9	Develop and use software (and file formats?) that can annotate 3D datasets with metadata and paradata	It is currently a challenge to ensure all relevant metadata and paradata are recorded and supplied, for research integrity and reuse. Especially for more complex models, a readme file is not ideal and (open) software through which 3D datasets could be annotated would be a much better solution.	E.g. eScience Center, PURE3D	
10a	Identify existing long-term storage solutions for 3D data or develop new ones.	It is often not clear what the best Trustworthy Digital Repository is for 3D datasets, and existing TDRs are not all prepared or suitable for 3D datasets. It is therefore important to identify which ones are or to work on making repositories ready.	To be decided; repositories	

10b	Adapt existing trusted repositories to large / 3D datasets.	Evaluate technical requirements, set up pilots with repositories, and share lessons learnt and best practices.	Repositories, e.g. DANS	
11	Gather information from the community and define clear policies on what to store for reuse.	It is currently not clear which parts of a dataset should be kept for long-term storage: the raw data / scans, the photographs, the model, all versions of the model, etc. What is needed also depends on the scope: what is the purpose and audience of the dataset. It is therefore important to find the minimal as well as optimal files that need to be retained in the long-term, specified by the purpose and audience.	Repositories, research support	
12	Enable reuse: set up a library with trusted / checked model items ready for integration into a model / virtual reconstruction.	In order to facilitate reuse of models or model parts it would be good to have one place to find information about, and ideally the actual model, ready for reuse. The metadata should also be available here, like the decision making processes, derivatives, etc. The aim is to easily find reusable model elements for reuse, to integrate in one's own model. See also Task 5, but this task is focusing on element level rather than project / dataset level.	To be decided	
13	Set up an open platform with an underlying repository where 3D models can be viewed and edited.	Like Sketchfab, but open / free / non-commercial, with more functionality, specifically catering to the needs of researchers. The latter can include features to make 3D scholarship acknowledged and recognised. A platform for viewing etc. is being developed by PURE3D; in the next phase such a platform would ideally have a seamless connection to a repository to have an integrated depositing process making depositing easier and quicker for researchers. To enable use	PURE3D, plus others	

		and reuse, the functionality to download datasets (i.e. from the repository) is key.		
14	Produce / update workflow and data management guidance for researchers, including guidance on access rights, licences, and 'ownership'.	Based on existing workflows and guidance, produce updated workflows and guidance specifically aimed at researchers with limited time. Tailor guidance to different disciplines and levels of technical expertise. Offer training and online resources. E.g. identify preservation intervention points within project workflows (CS3DP) & good-better-best recommendation (also see CS3DP).	Research support, (EU) projects	
15	Raise awareness and train a new generation of researchers	Develop a curriculum for data management in relevant educational programmes and offer internships/ fellowships in this field. One of the main limitations to good data management of 3D (and other) datasets is the lack of knowledge on how to do this and the lack of time that researchers have to spend on this. By raising awareness and training (early career) researchers good data management can be built into projects from the start which saves a lot of time and allows for budgeting for additional help, tools/software, and/or storage space.	Research support	
16	Set out clear guidelines for the preservation and reuse of 3D data in repositories	Trustworthy (certified) repositories already commit to long-term preservation, enabling access to, and curating datasets of all kinds. Such repositories can be recognised by a certification like the CoreTrustSeal. Based on the CS3DP, 4CH, and newly developed guidelines as indicated in this roadmap, it would be good to identify what this means for repositories in terms of 3D (cultural heritage) datasets (i.e. 'translate' the researcher and	DANS + others	

		project guidelines of Task 15 for repository use, providing case studies and examples).		
17	Contribute to the general re-valuing of research outputs discussion with 3D data use cases.	Document and publish use cases, engage in (academic) conferences, collaborate with journals and publishers to highlight the value of 3D data.	To be decided	

Acknowledgements

The workshop was part of the 4CH project (www.4ch-project.eu), which is a Horizon 2020 project funded by the European Commission under Grant Agreement n. 101004468 - 4CH. We are grateful to the workshop participants for their inputs during the workshop and to the presenters for their inputs prior to, during, and after the workshop. We also thank our multiple DANS colleagues who supported the workshop organisation and delivery, especially Hella Hollander, Samantha Willemsen, and Simon Saldner.

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Appendix I: List of workshop presentations

Pascal Flohr, René van Horik, Hella Hollander (DANS and 4CH project). Welcome, introduction to the workshop and introduction to the 4CH project.

Examples of 3D applications in research

Costas Papadopoulis & Susan Schreibmann (PURE3D, Maastricht University). PURE3D: An infrastructure for the publication & preservation of 3D scholarship.

Daniel Pletinckx (Visual Dimension). 3D for research: The case of virtual reconstruction.

Chiara Piccoli (4D Research Lab), ‘Reusing 3D models: Experiences from the *Virtual Interiors* and 4D Research Lab projects’

Data management of 3D datasets

Daniel R. Turner & Valentijn Gilissen (DANS), ‘Modelling Mycenaean chamber tombs with photogrammetry’

Maurice de Kleijn (eScience Center), ‘Mapping the Via Appia: About the software and data’

Kate Fernie & Henk Alkemade (CARARE), ‘Managing 3D cultural heritage: standards and metadata’

Coordination initiatives

Valentine Charles (Europeana), ‘Europeana & the common European Data Space for Cultural Heritage’

Bart Boskaljon (RCE) & Sanne Frequin (Utrecht University)

René van Horik (DANS, 4CH project), ‘The Competence Centre for the Conservation of Cultural Heritage (4CH)’

Appendix II: Web pages of projects and organisations which presenters are affiliated to

4CH project	https://www.4ch-project.eu/
4D Research Lab	https://4dresearchlab.nl/
Virtual Interiors project	https://www.virtualinteriorsproject.nl/
Vlooienburg project	https://4dresearchlab.nl/research/vlooienburg/
CARARE	https://www.carare.eu/en/
DANS	https://dans.knaw.nl/en/
e-Science Center	https://www.esciencecenter.nl/
Via Appia project	https://www.knir.it/en/onderzoeksproject/mapping-the-via-appia/ and https://via-appia.netlify.app/
Europeana	https://www.europeana.eu/en
PURE3D project	https://pure3d.eu/
RCE	https://english.cultureelerfgoed.nl/
Visual Dimension	http://visualdimension.be/