Maastricht University
September 2021

PURE 3D

Technical Report

Nick Fung, Research Software Engineer
Kelly Schoueri, PhD Researcher
Cristina Scheibler, Research Software Engineer

With feedback and additions by Costas Papadopoulos and Susan Schreibman

First Draft: 18 June 2021
Revision 2: 22 July 2021
Final Revision: 30 September 2021

Table of Contents

Section Authors

1. Executive Summary- *Kelly Schoueri*

2. Environment Scan- *Kelly Schoueri, Cristina Scheibler, Nick Fung*

   2.1 Literature Review- *Kelly Schoueri*

   2.2 File Formats- *Cristina Scheibler*

   2.3 Existing 3D Frameworks/Platforms- *Cristina Scheibler and Kelly Schoueri*

   2.4 Existing Repository Systems- *Nick Fung*

3. User Requirements- *Kelly Schoueri*

4. Guidelines/Recommendations for developing the PURE3D Infrastructure- *Nick Fung*

Appendix A- File Formats- *Cristina Scheibler*

Appendix B- Comparison of Repository Systems- *Nick Fung*

Appendix C- Survey Results- *Kelly Schoueri*

1 Executive Summary

3D research in and of itself is considered inferior to scholarly 'literature' because it is not text-based literature in the traditional sense of the term. Due to the complex nature of sharing and archiving academic 3D content, these types of data and knowledge are excluded as legitimate resources for research and education in the humanities and social sciences. To address this loss of knowledge sharing, the PURE3D Project was created as a solution by developing a 3D Web Infrastructure for 3D Scholarly Editions (3DSE) (see definition below) in which 3D scholarship is interactively made available to researchers, students, and the public. In so doing, such resources will be added to the scholarly ecosystem so that they may be valorised and preserved long-term. Without such a publicly accessible online space for research-based academic 3D assets, there is little to no chance of re-usability for these assets and the time and effort that went into producing them. Additionally, the value of a 3DSE for the public sector is an opportunity to demystify high-level knowledge regarding cultural heritage. Using innovative features for timelines and maps, levels of certainty, etc., the user can access and understand these models beyond simple navigation and clickable annotations. With a 3DSE, research is not buried within paywall publication and academic lingo, nor is it oversimplified in a short press release.

This PURE3D Technical Report is meant to provide a high-level state of the art summary on 3D scholarly web infrastructures. Section 2 of this report includes a brief environment scan of 3D issues, limitations, challenges, and recommendations based on a review of the scholarly literature, 3D file formats capabilities, 3D web platforms/frameworks and repositories systems. Section 3 is a summary of the user engagement activities that have been conducted thus far by the PURE3D team, namely introductory pilot partner interviews and a survey on user needs and requirements for 3D Web Infrastructures. Section 4 is a list of guidelines and recommendations for the entity model and architecture of the PURE3D Infrastructure. This section also includes next steps for the project.

TENTATIVE DEFINITION OF 3D SCHOLARLY EDITIONS

KNOWLEDGE SITES THAT PROVIDE A FRAMEWORK FOR 3D SCHOLARSHIP AND THE COMMUNICATION OF THE RESULTS, SPECULATIONS, AND THESIS OF AND AROUND THAT SCHOLARSHIP. THEY PROVIDE CONTEXTUALISATION AND ANNOTATION ABOUT THE 3D MODELS AND THE OBJECTS/WORLDS THEY REPRESENT.

THIS SCHOLARSHIP IS PRESENTED WITHIN A SINGLE SPATIO-TEMPORAL ENVIRONMENT THAT IS IMMERSIVE, MULTIVARIANT, AND MULTISENSORIAL.

2 Environment Scan

2.1 Literature Review

The scholarly literature for publishing and preserving 3D data on the web began in earnest with Koller et al.'s (2009) foundational work titled "Research Challenges for Digital Archives of 3D Cultural Heritage Models" based on a needs assessment survey conducted in 2006. From 2009 until today, similar literature has highlighted and reiterated these same issues, made recommendations and offered examples of solutions to some of these challenges as technology improves and becomes cheaper and more manageable for cultural heritage and higher education institutions. Alongside technical issues, additional literature addresses issues of 3D accessibility and sustainability for cultural heritage. Although not always explicitly stated, most professionals recommend that 3D web-based infrastructures adhere to the FAIR (Findable, Accessible, Interoperable, and Reusable) Principles (Wilkinson et al., 2016) as well as to the FAIR-EST (Ethical, Sustainable and Transparent) Principles (Hardesty et al., 2020).

Below is a high-level summary of the most important topics regarding the development of a 3D web infrastructure with a selection of the most important issues, recommendations and solutions as highlighted by the literature from 2009 until mid-2021. These topics include: defining 3D data and the challenges of publishing this type of media on the web; the importance of attaching metadata – detailed, rich information and associated media – to 3D content for purposes of contextualization and searchability; producing a framework that facilitates long-term accessibility of these 3D data and information; and recognizing that quality management is required to ensure accuracy and scientific transparency for expert and non-expert communities.

2.1.1 3D Data

A 3D model is a computer-generated mathematical representation of an object in three-dimensions (x,y,z). We can thus describe *3D data* as the stored geometrical equations that are read by the software of a viewing platform to visualize the *3D model*. 3D models are composed of vertices (x,y,z locations), edges (line connections between the vertices) and faces (a flat surface inside at least three edges) (Figure 1). 3D data may also include other information to translate the model, such as properties relating to material textures and their opacity, reflectiveness, shadow occlusion, or animation properties.

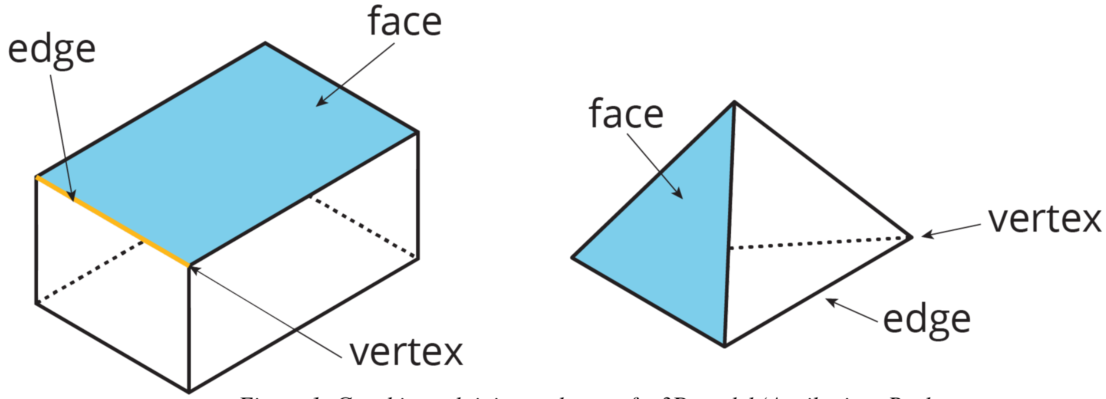


Figure 1: Graphic explaining make-up of a 3D model (Attribution: Peakstore, https://www.pngitem.com/middle/ibbTTwi_picture-vertex-edge-and-face-hd-png-download/)

Early attempts to publish 3D content on the web faced two initial debilitating issues: 1.) lack of a secure, feature-rich file format (Koller et al., 2009); and 2.) inability to transmit and render large, detailed datasets (Potenziani et al., 2018). For the first issue, Champion (2016) recommends that CH projects avoid proprietary 3D formats. They should instead adopt shared, open and standard file formats, such as .OBJ, .X3D, .PLY and .glTF. Nabil et al. (2011) define an open file format as:

> a digital format whose specifications are freely available to the community, are maintained by authorities (in particular, universities, research centers and foundations), and are based on specific legislation that protects and guarantees the continuity…according to the general policy that any change to the source code will be made available to the public in the same way in which it was received (p. 11).

Additionally, open formats facilitate a 3D model's long-term preservation by means of a continuous data-transfer to up-to-date software solutions (Nabil et al., 2011).

With regard to web-handling of large projects, Champion and Rahaman (2020) suggest that at least two file formats should be generated for a project: a high-resolution one for archiving and a simpler, smaller one for online viewing. An example of an open-source product that can achieve these two versions is that of the ARIADNE Visual Media Service (Ponchio et al., 2016) in which users can convert raw data files into a web-compliant and efficient format. However, the Visual Media Service (http://visual.ariadne-infrastructure.eu/) is not a repository for storing and maintaining this 3D content online. Alternatively, the 3DHOP platform (https://www.3dhop.net/) has a solution for rendering single high-resolution models (usually derived from photogrammetry and 3D scans) in which a Nexus multi-resolution approach is used to adapt to different levels of detail as the user moves about the model. While this is a streamlined way to publish a singularly dense 3D model, the limitation on this approach is that 3DHOP is not suited to multiple low-poly objects within one scene (Scopigno et al., 2017).

Within the context of moving forward with PURE3D, the literature makes clear that at least one, if not more, commonly used open file formats should be uploaded to the 3D web infrastructure. This would ensure that file conversion and translation is easier and lossless with future software upgrades. With regard to file density, since PURE3D's focus is not on high-resolution viewing of a single digitized object, but rather either a collection of single objects or a scene of multiple 3D objects and environment settings (virtual world), we may adopt either one of the two solutions: 1) a downgraded single web-only version; or, 2) the two-version solution: a web-friendly resolution of a 3D model or models and a high-resolution version that can be downloaded for viewing with an offline desktop software.

2.1.2 Metadata

Metadata attached to digital media is cited as one of the top priorities when publishing 3D content online (Koller et al., 2009). According to Hansen and Fernie (2010), specialized metadata is needed "to support the description, preservation and discovery of the 3D/VR models produced in the archaeology/architecture domain" (p. 460). Clarke

(2015) stresses that detailed metadata is essential for data reuse "so that future scholars are able to determine any potential biases in initial collection as well as the quality of the resulting analyses" (p. 315). In addition to a cultural heritage suitable and widely adopted metadata schema, Champion (2016) recommends "an ontology of model components so we can find and label individual parts, a storage and retrieval system for the 3D models and a way of linking the models with external assets (other media as well as publications and papers) (pp. 3–4).

With regard to a metadata schema, The PARTHENOS White Paper from 2016 (Alliez et al., 2016) recommends that the adopted schema identifies information relating to Actors, Objects, Goals and Tools:

- Actors: the agents involved in the creation, modification, maintenance, enrichment and critique of 3D models. They play a crucial role in the understanding of a 3D object as they provide the original knowledge of its creation and may hold valuable additional data for the interpretation and reuse of the model.
- Objects: Aside from the digital object itself, the objects of which the 3D object is a model and their aspects are of key importance in order to be able to understand and evaluate the information delivered by a 3D model.
- Goals: 3D models are elaborated towards some end. They do not form and cannot be seen as digital replacements of the actual objects of which they are models. Rather a 3D model plays a functional purpose in a scientific process to understand some aspect of an object. Explicitly documenting such goals of creation/modification/use of models is crucial to their scientific evaluation
- Tools: Playing an effective causal role in the produced model are the sampling devices and the digital tools adopted for the digitization, as well as their use at certain moments in certain environments using specific variables. Linking 3D models to the causal processes that created them is crucial in supporting their interpretation and reuse (pp.47–48).

Some of the best-known existing schemas include Dublin Core, CIDOC-CRM, CARARE and CHML (Cultural Heritage Markup Language). While Dublin Core (https://dublincore.org/) has basic elements that can be widely applied to a diverse set of fields, it lacks specificity for the cultural heritage sector. Which has led to other initiatives such as from CIDOC-CRM (http://www.cidoc-crm.org/) in 2006 to define a semantic glue between different sources of information in the documentation of cultural heritage. Inspired in part by CIDOC-CRM, CARARE (https://www.carare.eu/en/) from 2010-2013 expanded the schema for the fields of archaeological and architecture heritage and is used by a number of repositories, cultural institutions and universities (Hansen & Fernie 2010). Cultural Heritage Markup Language (CHML) is a proposal for a holistic approach to describe digital 3D reconstruction projects using an ontology that adds to CIDOC-CRM by also describing "provenance information and paradata, and the mapping (labelling) of geometrical, material, and lighting characteristics in the source text (for long-term archiving purposes)" (Kuroczynski, 2014, p. 4) in addition to basic CH metadata (see also, Hauck & Kuroczynski, 2015; Kuroczynski et al., 2016). A similar and more recent initiative from the US is that of the LIB3DVR working group that will soon publish (in 2021) a book on 3D standards (Hardesty et al., 2020).

For the PURE3D platform, CHML is interesting because it is a specialized expansion of the CIDOC-CRM schema for CH objects from the 3D reconstruction point of view (Hauck & Kuroczynski, 2015). However, technical support for this schema seems to have ended and we will need to see what aspects (if any) can be adopted. Another important consideration is our project partners. It appears that some PURE3D partners (e.g., DANS and Erfgoed Leiden) have adopted the CARARE schema in their work. It is recommended as a future step to discuss with all pilot partners about which system they use and if they are satisfied with this for their 3D projects.

2.1.3 Searchability and Findability

With a robust and established metadata schema, 3D content and virtual worlds will have more diverse and reliable search functions that allow for it to be traceable, linked to previous works and to related scholarly information (Champion, 2016). Kubik and Kwiecien (2021) emphasize that digital repositors should offer "a user-friendly graphical interface enabling easy search for records, classification and sorting of search results, content preview and retrieval of items" (p. 1). Hardesty et al. (2020) suggest that searching can also happen within the VR environment for an immersive and organic experience different from the traditional "Search Within" functionality (p. 796). Statham (2019) suggests search functionality that is unique to the field of cultural heritage such as categories (culture, country, map or timeline), keywords, most recent, most popular or model features (e.g., download enabled, animations, VR, etc.). She also recommends that users can search for content that has been supervised by a historian or is part of a specific project. To this we may add 3D content that has been peer-reviewed or included as part of a publication.

Findability of 3D projects is another challenge that the Digital Cultural Heritage sector is facing. A solution proposed by Champion and Rahaman (2020) is to assign a DOI (digital object identifier) to each model as well as potentially to subcomponents or annotations. While DOI's are obligatory for scholarly articles, they are less common for 3D projects and assets. However, as the use of 3D content for scholarship and research grows, there is a need to assign these identifiers to 3D data so that they may be properly referenced and therefore become findable on the web. For example, Sketchfab (https://sketchfab.com/) automatically generates a Unique ID (UID) by attaching a string of unique characters to the end of the hosted model's URL link.

Searchability and findability are key considerations in design and development of the PURE3D infrastructure. Having search functions at different levels of the infrastructure should be carefully considered moving forward. Additionally, the project team should determine how and to what degree projects, sub-components and annotations are given unique ID's.

2.1.4 Accessibility and Rights Management

Accessibility has two different connotations: 1.) access which is determined by technology, businesses and/or organizations (high-speed internet, hardware and software, publisher paywalls, institutional login credentials, etc.); and 2.) access which is based on a potential variety of personal limitations (language, technical literacy, user-friendliness, physical and learning disabilities, etc.).

While it is always recommended that access to digital resources be free and without limitations, sometimes this is not possible as information can be proprietary, unpublished, or sensitive in terms of location, culturally specific laws, individual privacy rights, etc. Therefore, many services choose to allow data creators to have granular copyright and licensing agreements on individual items (Clarke, 2015). For 3D data, it may be the case that a selection of 3D projects are designated as access-only. In other words, an end-user is only allowed to view and navigate a 3D object but is not permitted to download and re-use the data (Hardesty et al., 2020).

The second meaning of accessibility can be from the human-machine perspective. Kubik and Kwiecien (2021) define this kind of accessibility as:

> a feature of designed products, devices, services and environments related to their adaptation to the needs of users with diverse abilities and manifested either directly or through the use of assistive technologies (p. 5).

Therefore, it is generally recommended that 3D content can be accessed on different devices, including Android and iOS mobiles, tablets, VR devices, laptops and desktops computers (Statham, 2019). Additionally, across all these different platforms the interface should be intuitive and responsive, even for the visually and hearing impaired.

PURE3D should recognize that a research project may want to allow their materials to be accessible to the wider public and yet still have some security and protection against copyright infringement. Therefore, the PURE3D infrastructure may adopt a granular approach to access and rights management. Additionally, updated methods for intuitive human-computer interface design should be studied, implemented and refined based on user studies. Ways that we may accommodate disabilities is to have screen-reader friendly annotations.

2.1.5 Conclusion

This literature review has only briefly scratched the surface of the challenges and solutions for publishing 3D content on the web. There are problems relating to the models themselves as they tend to be dense, complex and not easily transferable from the modelling software to online viewers. Metadata standards for 3D Cultural Heritage are not fully defined and so this will be a challenge to adopt a one-size fits all solution. Finally, finding and accessing reputable 3D content for research purposes is not yet standardized for the cultural heritage community and thus these projects exist in a vacuum of digital space, disparately spread across the web.

2.2 File Formats

A 3D file format is used to store geometry, appearance (e.g., materials and texture), scene (e.g., light, environment) and, if available, the animation of a 3D object in plain-text form or in binary form. 3D file formats can be divided into two types: proprietary and non-proprietary. The former term is used to describe a native file format from software applications (i.e., those generated from particular software and can only be accessed via that – in most cases paid – software), while the latter describes free and open-source file formats (Nishanbaev, 2020). Closed or proprietary formats can cause problems in terms of access, reliability and longevity, and the resulting models can lack a range of desirable features (Koller et al., 2009).

A study by McHenry and Bajcsy (2008) confirms the existence of more than 140 file formats for 3D models. As mentioned earlier, Koller et al. (2009) identified the absence of a shared, secure, and feature-rich file format for 3D models as being a major obstacle in virtual heritage projects at the time of writing. However, a recent survey conducted by Sketchfab (Sketchfab, 2019) determined that .glTF and .PLY formats are increasingly being used by heritage communities.

Among the many open-source formats, X3D, COLLADA and OBJ are the most used for modelling 3D objects. Two of them are ISO standards (X3D and COLLADA) and one is a Khronos Group standard (.glTF). The Khronos Group is a consortium responsible for the creation of advanced, royalty-free interoperability standards for 3D graphics, augmented and virtual reality, parallel programming, vision acceleration and machine learning.The proprietary file format .3ds, from AutoDesk's 3ds Max software, is also commonly used by the heritage sector for the creation of 3D objects. Further detailed information about each file format can be found in Appendix A.

Some institutions linked to archaeology, preservation of historical data, policies, and standards for digital data have recommendations on file formats for use and preservation of 3D models. Table 1 summarizes the recommendations from the Archaeology Data Service (Service, 2020), Europeana (Europeana Network Association Members Council, 2019), Khronos Group (The Khronos® Group Inc., 2020) and IANUS (IANUS, 2020) for using each file type format to preserve of 3D content.

File Format	Archaeology Data Service	Europeana	Khronos Group	IANUS
VRML	✓	✗	✗	✗
X3D	✓	✓	✗	✓
COLLADA	✓ [1]	✗	✗	✓
OBJ	✓	✓	✗	✓
3ds	✗	✗	✗	✗
ply	✓	✓	✗	✓
gLTF	No recommendation	✓	✓	No recommendation

Table 1 Recommendations for preservation of 3D content

For the PURE3D project, the recommendation is to follow the open standard format. The exact file formats that will be supported by the platform will be chosen based on the user survey and the results of the focus groups.

2.3 Existing 3D Web Platforms/Frameworks

The first methods of publishing 3D content on the web required partial or exclusive use of add-ons beyond the software and the browser, like the Macromedia Flash Plugin released in 1996, Apple Webkit CANVAS and Adobe Flash. Until the release of WebGL in 2009, the web landscape was populated by a series of proprietary systems, third-party software and closed solutions. It was due to this lack of a common and recognized development standard that led to a heterogeneous set of approaches for 3D graphics on the web (Potenziani et al., 2018).

Because of this lack in standardization and the diverging implementations, 3D content was not considered a medium suitable for the Web. That is, until the release in 2009 of the WebGL application programming interface (Khronos Group, 2021). This breakthrough kickstarted the rapid growth of a new generation of applications, based on a common standard, that were able to act directly on the rendering pipeline and were supported by all common web browsers.

WebGL is a web-specific version of the royalty-free OpenGL graphics API (more specifically of the restricted embedded systems API, OpenGL ES 2.0 (Khronos Group, 2021), and allows access to dedicated graphics processing hardware (the GPU) directly

[1] Suitable for preservation and recommended for 3D content where x3d is not an option.

from the browser (via JavaScript). This makes WebGL extremely optimized and computationally light, and thus ideal for the web (Potenziani et al., 2018; Evans et al., 2017).

The current approach in web-based visualization is to exploit the power of GPUs through WebGL and HTML5 technologies for GPU-accelerated client-side rendering within the browser without plugins. GPU-based visualization techniques help to improve rendering performance and interactivity by off-loading to the GPU expensive computations, which would otherwise be unfeasible on the CPU using JavaScript. Client-side rendering is preferred because it avoids the round-trip network latency suffered by server-side rendering approaches that require changes in rendering or visualization parameters to be sent to the server to generate new images (Mwalongo et al., 2016).

The WebGL revolution opened many possible uses for 3D content on the web. Several characteristics of local tools were mapped to web applications through engines, libraries, and frameworks, such as three.js (https://threejs.org/), Babylon.js (https://www.babylonjs.com/) and A-Frame (https://aframe.io/). Of the many functionalities now available online, the cultural heritage sector makes use of these tools for the visualization and communication of 3D models.

2.3.1 Web Viewers

The visualization and inspection of 3D models on the web is usually done through a web viewer, built on top of WebGL and HTLM5. Despite a growing number of initiatives related to 3D web publishing, there is not yet a consistent methodology for visualizing 3D models together with "research sources and derived multidisciplinary explicit assumptions" (Giovianni, 2020).

Due to the lack of definition of standards for the visualization of 3D objects on the web, not all viewers present the same features, as noted by Champion & Rahaman (2020). Based on their survey for relevant features from eight institutional and eleven commercial online 3D repositories in the scholarly field of 3D digital heritage, they elicit some functionalities that a web viewer for 3D models should present:

- Zoom and rotation: to allow observation of specific detail and overall understanding of the 3D model.
- Walk around or walk through outside or inside of the model: to have a sense of scale and perceive the object/space according to the viewers' perspective.
- Add or remove parts of the 3D model: to help virtual reconstruction of a conjectural model and online collaboration.
- Wireframe and texture view: to allow the user to view the 3D model under various viewing conditions (solid, shaded etc.).
- Take screenshots: to allow the user to take a screenshot while focusing on a certain perspective or zooming on specific detail.
- Annotation of text/image: to annotate information or media (text, image, sound etc.) on the 3Dmodel.
- Change the field of view: to help users to view the 3Dmodel/space from various perspectives/angles/locations.
- Measure the 3D model: to help scientific investigation.

- Download of the 3D model: to offer a range of file formats for download as well as the model in its native format.
- Timelines: to show how the model changes over time. Helpful feature for archaeological research.
- DOI (digital object identifier) of the 3D model: to provide unique identity and to be cited/refer easily (Champion & Rahaman, 2020, p. 5).

To add to these, the 2016 PARTHENOS White Paper (Alliez et al., 2016) suggests that web viewers should move beyond plain visualization and include features for more structured analysis:

- Dynamic lighting: the user should be able to easily modify the direction of light (grazing light inspection, in real time).
- Non-photorealistic lighting and rendering: to allow the production of rendered images that resemble the manual drawings or the illustrations (so common in archaeology or restoration).
- Cut-through sections and export profile as independent assets.
- Produce maps and sections from the 3D model, in formats ready to be used by other applications.
- Detect similarity, symmetry, or orbits in a single model or between different models.
- Record/freeze the camera position of specific views (like a landmark) and visualization of the model using different shaders or rendering parameters.
- Compute the volume between the different layers in the sampling of an archaeological excavation.
- Automatic and user-assisted partitioning of a model or a scene.
- Exploded views: useful in the case of complex objects, built over several components.
- Space warping approaches for enhanced visibility and inspection: to allow presentation in a single visual space the decoration or incision wrapped over a solid object.
- Automated discovery of correlations between different objects.
- Compliant transparent rendering (Alliez et al., 2016, p. 36).

The following subsection details the main characteristics and features of four open-source web viewers developed for and used in the heritage sector for visualization and inspection of 3D models.

2.3.1.1 ATON

ATON is a framework based on Node.js[2] and Three.js[3] designed and developed by a team at the Institute of Heritage Science from Italy's National Research Council (CNR ISPC) to create Web3D/WebXR applications interacting with Cultural Heritage objects and 3D scenes on the Web (Figure 2). Besides visualization of the 3D objects, it allows for 3D semantic annotations (including text, video, image and sound), different navigation modes, VR mode, Physically Based Rendering (PBR), setting of custom viewpoints, multi-temporal visualization and lighting customization. The framework also provides multi-user collaboration and annotation on 3D scenes.

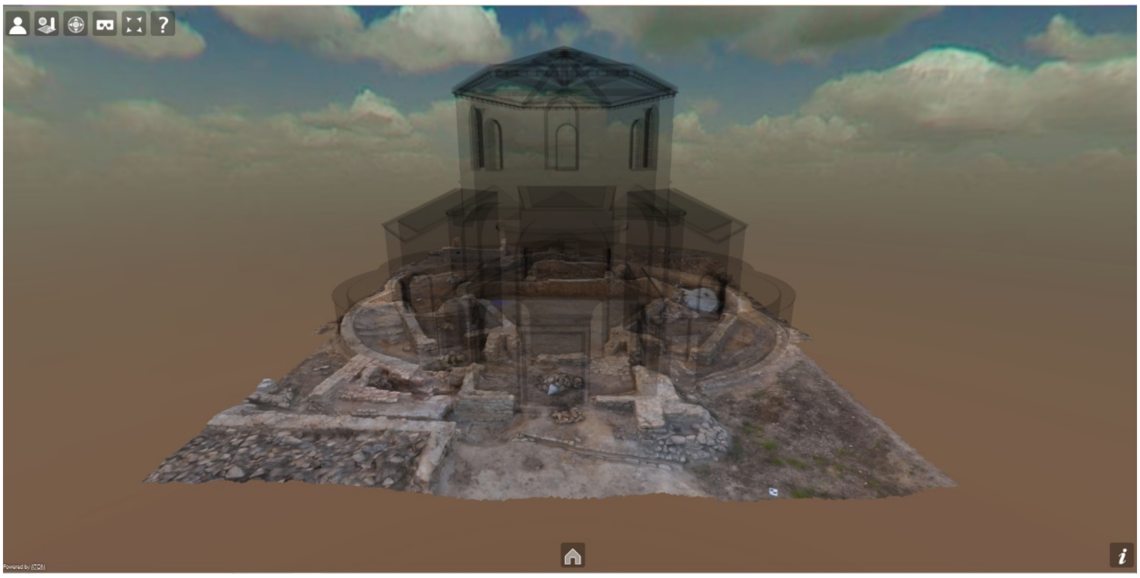


Figure 2: ATON web viewer

The open-source framework is available on GitHub, where it is possible to download the source code with some examples of its functionalities. The project's website (http://osiris.itabc.cnr.it/aton/) provides links to the documentation and Telegram group, with the goal to enable further discussions about the project and its implementation.

The ATON viewer does not provide a built-in editor for scenes or objects, forcing the user to adapt/change its files to the format used by ATON before uploading them to the viewer. This may create a few issues as many users are not familiar with the properties of the JSON format of the scene/object files and may not know how to manipulate them. The multi-temporal visualization is part of another project derived from ATON's main source code, EMviq (Fanini et al., 2021), and must be downloaded and installed independently.

The documentation on the project's website allows for the basic examples to be built and run on a local machine, despite being deprecated in relation to the latest code version on Github. Documentation and tutorials for the most advanced features, such as the multi-temporal visualization, editing and saving of annotations, are not available. For the complete use of its features, a user/developer must spend some time gathering knowledge

[2] Node.js® is a JavaScript runtime built on Chrome's V8 JavaScript engine. (https://nodejs.org/en/)

[3] Three.js is a JavaScript general purpose 3D library. (https://github.com/mrdoob/three.js/)

about the inner workings of the framework, before being able to customize and expand it.

2.3.1.2 Smithsonian Voyager

Smithsonian Voyager is part of the Smithsonian's Digitization Program Office's 3D foundation pipeline (Figure 3). The Voyager web explorer has been created specifically for displaying, exploring, and sharing rich 3D data and models from museum collections and cultural heritage. The Smithsonian pipeline for web viewing is composed of the Voyager Explorer and the Voyager Story, a tool for quality inspection, authoring of annotations, articles, and tours. (Smithsonian Digitization, 2021).

The Voyager Story targets curators and 3D technicians, providing editing of model views, material settings, lights, camera, and environment. It also allows the creation and editing of annotations, which can be enhanced by the addition of documents, media, tours, and snapshots. It uses its own JSON file format for the scene (Voyager SVX Documents) and supports 3D content in the .glTF/.glb format.

The open-source framework is available on Github (https://github.com/Smithsonian/dpo-voyager) and documentation can be found on the project's web page (https://smithsonian.github.io/dpo-voyager/). The code provides assets and examples of its main functionalities, allowing for the web viewer to be built and run easily on a local machine. The documentation also provides a template of its own file format, used for the creation and editing of 3D scenes.

The processing of the 3D model files to the framework format can also be done through a tool provided by the Smithsonian, called 'Cook' (https://smithsonian.github.io/dpo-cook/). Implemented as Node.js server, it can be controlled via web API, a web user interface, or via command line tool. The Smithsonian also provides a prototype of a repository called 'Packrat' (https://github.com/Smithsonian/dporepo), which is scheduled for a release and update soon.

Figure 3: Smithsonian Voyager Web Viewer

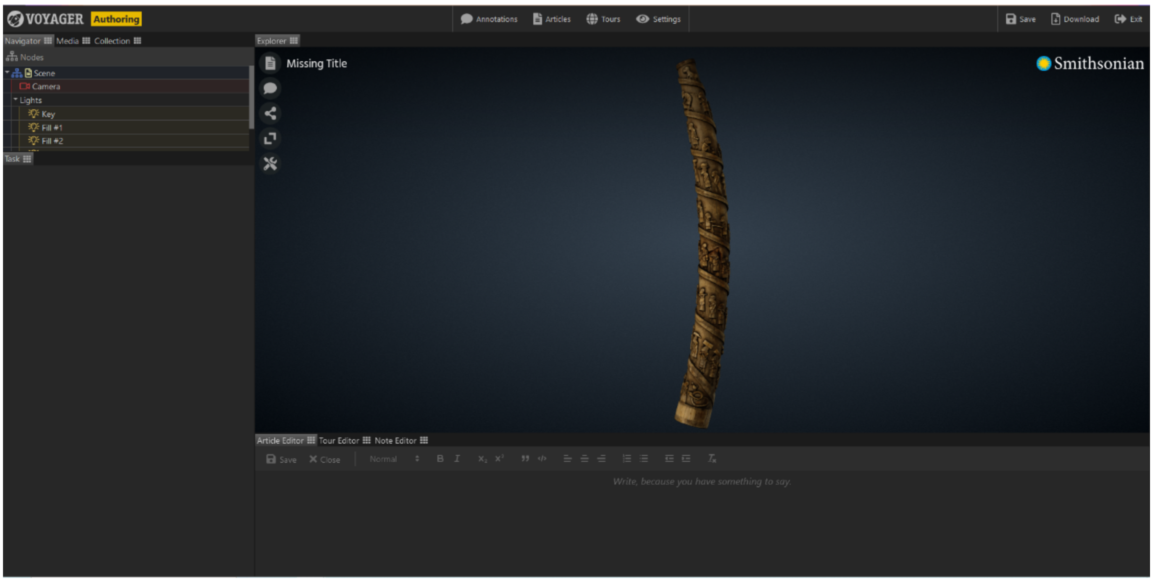


Figure 4: Smithsonian Voyager Story

2.3.1.3 3DHOP

3DHOP is an open-source software package for the creation of interactive web-based presentations of high-resolution models, oriented to the Cultural Heritage field (Figure 5) (ISTI - CNR, 2021). By using multiresolution encoding, it can efficiently stream high-resolution 3D models, providing a series of ready-to-use templates and examples tailored to the presentation of cultural heritage artefacts (Potenziani et al., 2015). It allows for the creation and editing of annotations, light settings, custom camera positions, Physically Based Rendering (PBR), mesh and material views, and loading of multiple 3D objects on the same scene.

3DHOP has been integrated in several cultural heritage and archaeological projects, such as:

- ADS 3D Viewer from Archaeology Data Service (https://archaeologydataservice.ac.uk/research/3DViewer.xhtml),
- Global Digital Heritage (https://globaldigitalheritage.org)
- MorphoMuseuM (M3) (https://morphomuseum.com)
- The Swedish Pompeii Project (http://www.pompejiprojektet.se/)
- Balsagnano Project (http://www.casaledibalsignano.it/).

Figure 5: 3DHOP Web Viewer

2.3.1.4 Kompakkt

Kompakkt (https://kompakkt.de) is an open-source online-tool for linking 3D objects to multimedia content and for gathering information through annotations in 3D space more generally (Figure 6). It enables users to share, explore, and collaboratively annotate objects in standard modern web browsers. The 3D representation of an object serves as the hub of an open-ended collection of heterogeneous information established through the use of multimedia annotations. The annotations are flexible (meta)data complementing what one usually finds in collection management systems in the GLAM sector (Eide, 2019).

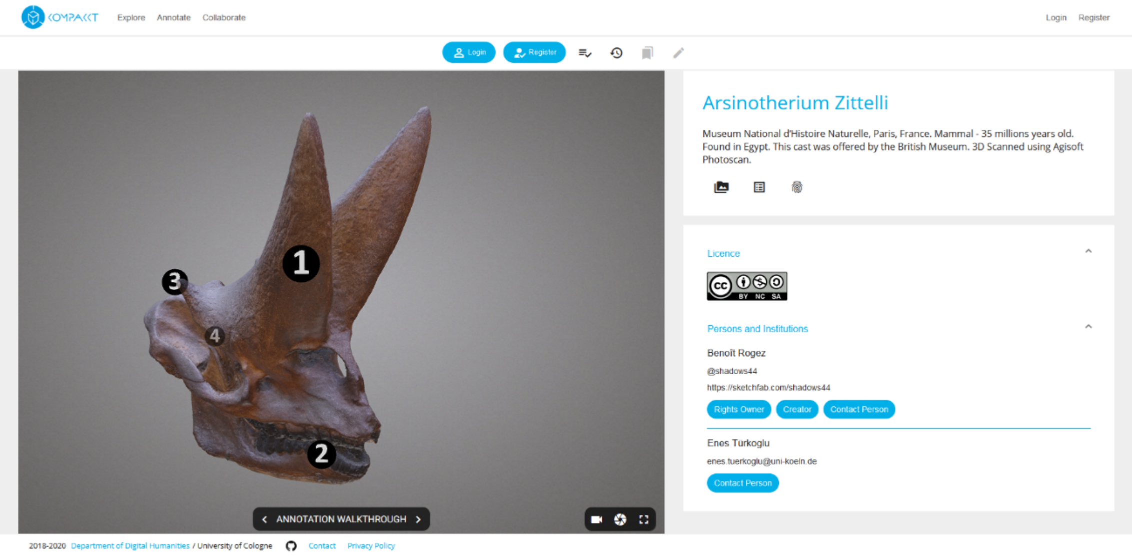


Figure 6: Kompakkt Web Viewer

2.3.1.5 Virtual Interiors

The Virtual Interiors as Interfaces for Big Historical Data project (https://www.virtualinteriorsproject.nl/) began in January 2019 and is financed by an NWO Smart Culture – Big Data / Digital Humanities grant with a focus on spatially enhanced publications of the creative industries of the Dutch Golden Age. As of July 2021, the project has a working prototype using an interior reconstruction of De Graeff's *voorhuis* (entrance hall) to demonstrate the functionalities of their 3D research environment. Currently, the project team has a working prototype based on BabylonJS[4] but they are working on redeveloping the viewer with a three.js framework. Public and private communication is that the framework and source code will be available for open-access use in the near future (Huurdeman & Piccoli, 2021) and that the project is willing to open channels of collaboration with the PURE3D project (private email correspondence). Although the research environment prototype is custom-built for a specific project, the development team intends to extend the prototype "into a more stable and sustainable, and where possible more generic, form" (Huurdeman & Piccoli, 2021, p. 331).

The Virtual Interiors development team created the web application using HTML5 and Javascript with BabylonJS for the underlying back-end library of the 3D reconstruction (Figure 7). Custom built JavaScript extensions were built for custom research functionality and integrating necessary data and settings while the user interface was created using Bootstrap (https://getbootstrap.com/), an open-source front-end toolkit which allows for responsive user interfaces (Huurdeman & Piccoli, 2021, pg. 330).

[4] https://3d-demo.virtualinteriorsproject.nl/index.html?app=pdg-entrance-hall&fps=30#

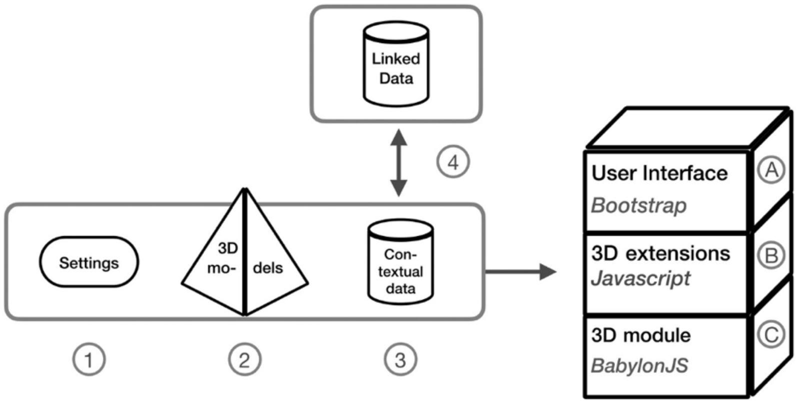


Figure 7: Virtual Interiors web viewer structure (Huurdeman and Piccoli 2021)

This framework allows for settings, 3D models and contextual data to be deployed within the infrastructure.

- Settings contain camera positions, default lighting conditions, the paths to the 3D models and other necessary configurations
- 3D models are uploaded in the GLTF format
- An editable online spreadsheet in the CVS file format is automatically read by the application to store and collaboratively edit the contextual dataset containing metadata and paradata
- Linked Data identifiers are used within the database to integrate and connect to external data sources

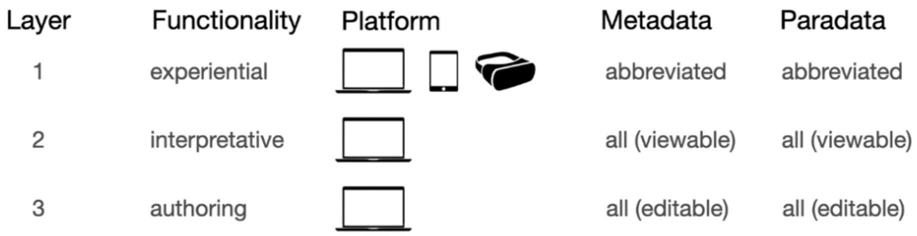


Figure 8: Virtual Interiors Interaction Layers (Huurdeman and Piccoli 2021)

In order to avoid a tool that is over-generalized in order to cater to everyone and thus is of no use to anyone, the Virtual Interiors team opted for "a standard, lightweight set of features, which can be extended for use in different contexts" (Huurdeman & Piccoli, 2021, p. 330), modelled after Shneiderman's (2002) "multilayer approach". These features are subdivided into three layers of user interface features that can be deployed on different devices and with increased functionality, metadata and paradata at each consecutive layer (Figure 8).

<u>Layer 1</u>

- Supported on Desktop, mobile and VR platforms
- Real-time exploration of a 3D Environment aimed at any end-user
    - Abbreviated metadata and paradata
    - Different camera settings (e.g., orbit and first-person views)
    - Interaction with elements in the scene
    - Different ways to move around and explore the 3D scene

Layer 2

- Supported only on Desktop platforms
- Additional features targeted at research and interpretation aimed at scholars
    - Access to all metadata and paradata
    - “Details” sidebar tab consists of descriptive metadata about the original object, the reconstruction, and the 3D model (Figure 9)
    - “Linked Data” sidebar tab includes in-viewer resources as well as links for external browsing possibilities; including thumbnails of related works of the same type and/or time period or works by the same creator of the original object (Figure 10)

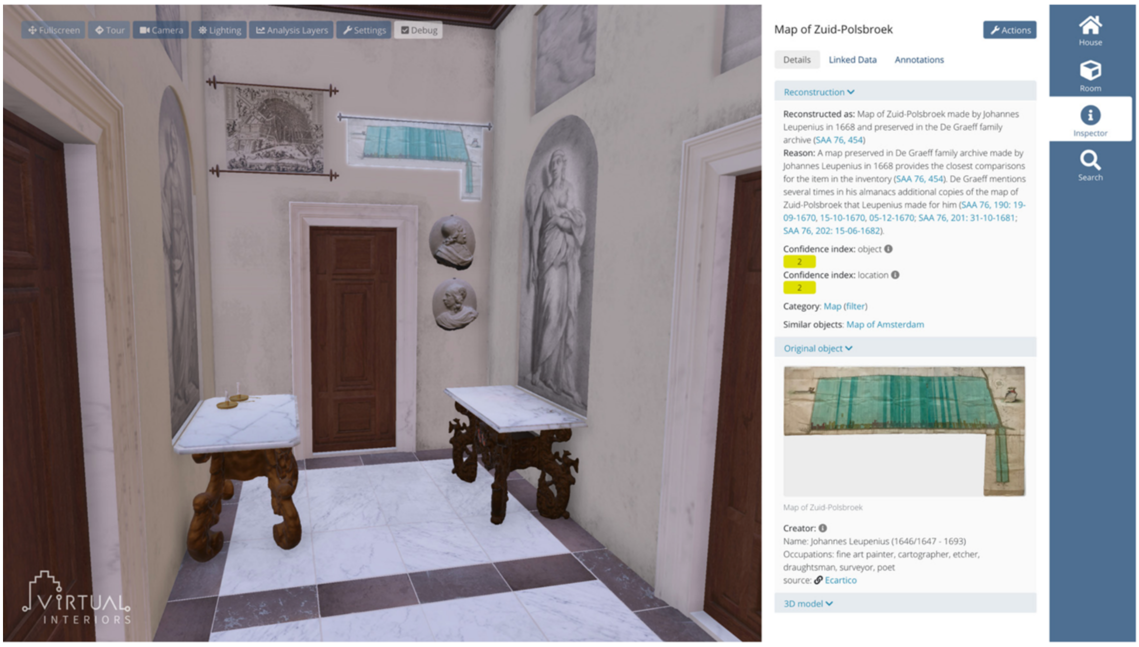


Figure 9: “Details” Sidebar Tab (Huurdeman and Piccoli 2021)

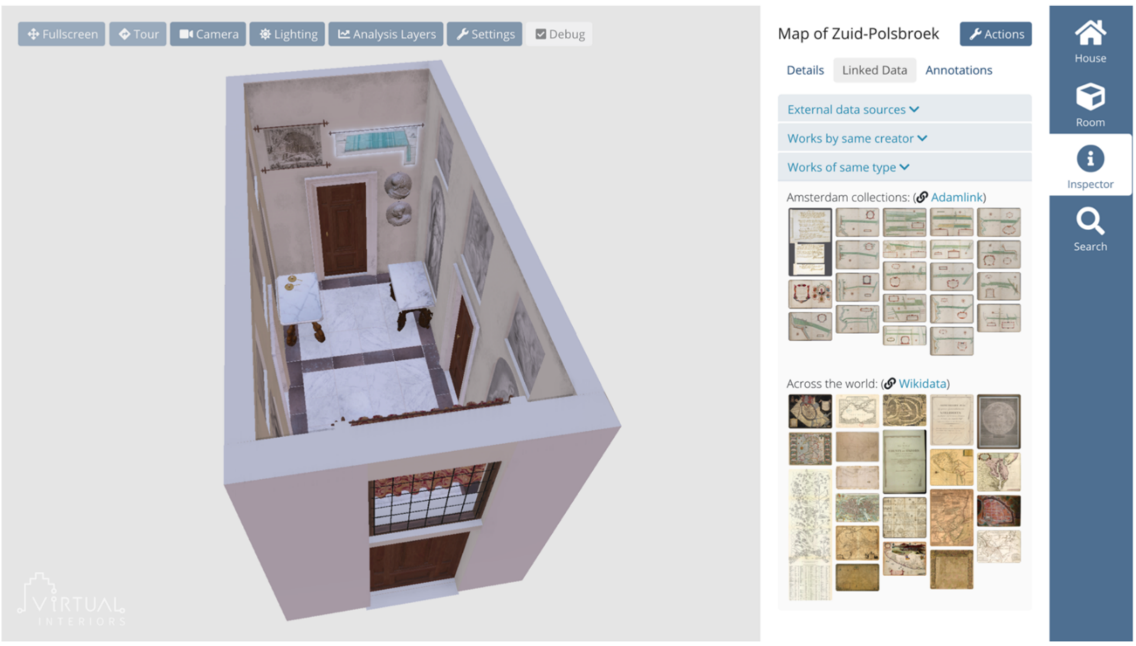


Figure 10: “Linked Data” Sidebar Tab (Huurdeman and Piccoli 2021)

- In addition to exploring external information, users can customize, highlight, and selectively emphasize objects and spaces within the 3D scene itself, manually or via an included textual search function.
- Mouse-over Color-coded confidence indices on both the object's reconstruction and the location in the reconstructed space; index ranges from 1 (certain) to 4 (uncertain)
- Color-coded overlay can be superimposed over the entire 3D scene, allowing for direct inspection of certainty while navigating the 3D scene (Figure 11)
- From 'Actions' menu, a user can toggle between different hypotheses
- Support two types of explorations: of lighting conditions, and of custom hypotheses related to the placement and spatial arrangement of objects. Users of the prototype can apply predefined lighting hypotheses.
- By using the native "inspector" of the used BabylonJS framework, experienced users can also perform custom experimentations with lighting settings, shadow generation, and lighting arrangements, to explore what a space looked like in different lighting conditions
- Allow for rearrangement and customization of included 3D objects, as this may enhance learning and engagement (Figure 12)
    - Users are allowed to rearrange objects in the room. An object can be freely moved, scaled, or rotated.
    - Visual filters and viewing modes can be applied to the object via the "Actions" menu.
    - Categorized object colour views are available via the "Analysis layers" option. Thus, users can potentially explore different hypotheses with regard to spatial arrangement of objects as well experiment with their appearance.

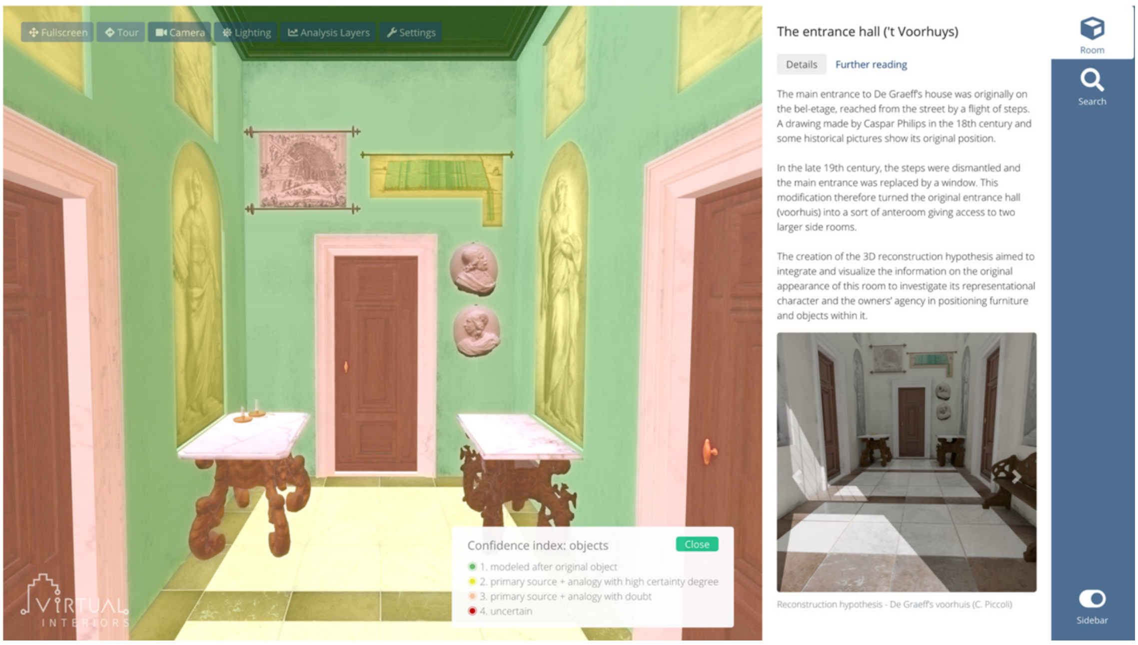


Figure 11: Color-coded Certainty Overlay (Huurdeman and Piccoli 2021)

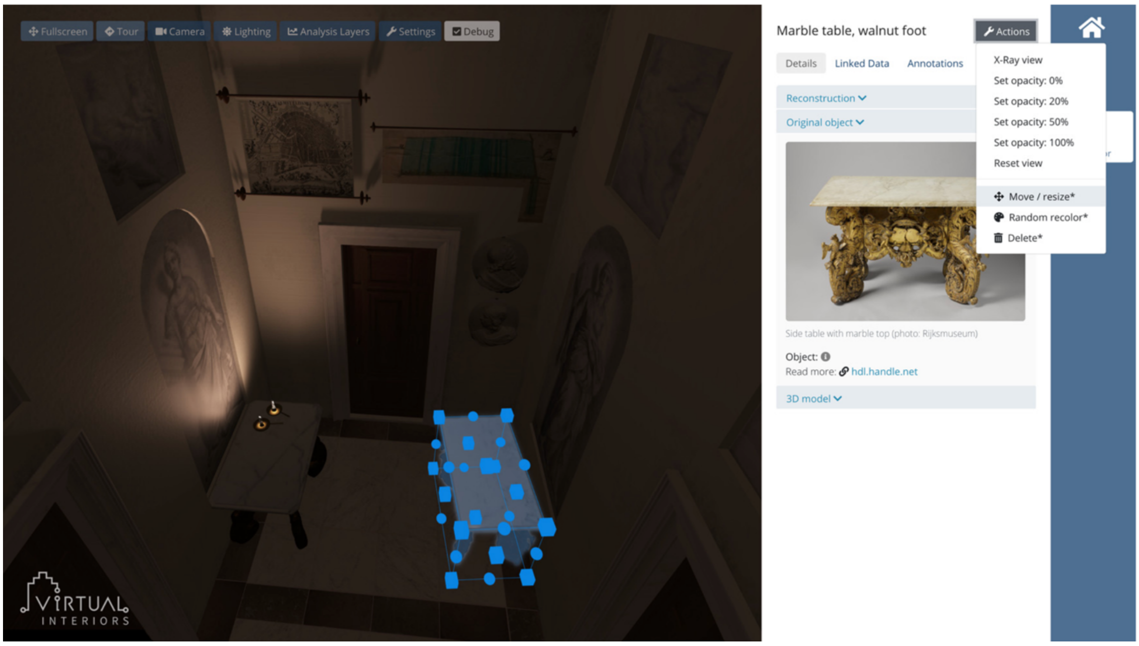


Figure 12: Example of object rearrangement (Huurdeman and Piccoli 2021)

<u>Layer 3</u>

- Supported only on Desktop platforms
- Adds functionality to do authoring
  - Direct editing of metadata and paradata by authors of the 3D environment
  - end-users such as scholars, reviewers, heritage professionals, educators, or the general public, may create annotations within a 3D virtual environment to add their impressions, interpretations, comments, and suggestions either explicitly or implicitly[5]
  - Not yet implemented but there is an intention to develop a system for eliciting expert feedback, for instance to formally approve the correctness of reconstructions or associated metadata.
  - Support textual annotations at the level of logical spaces and objects
  - Two or more annotations can be linked together to create a narrative or an "intellectual guided tour" through the materials, with the possibility to associate camera viewpoints, viewing modes, and analysis layers with each annotation.

[5] An explicit annotation is a specific act of adding an annotation to an object by a user, while implicit annotations are for instance interaction sequences, clicked items, and navigation within the 3D space. These implicit annotations can be monitored by the underlying system and presented to a user, at an individual or aggregated level. (Huurdeman and Piccoli 2021)

2.3.2 Comparison of Features Available on Aton, Smithsonian Voyager, 3DHOP, Kompakkt and Virtual Interiors

This section presents a comparison table of features from the Smithsonian Voyager, ATON framework, 3DHOP, Kompakkt and Virtual Interiors according to the guidelines outlined in Champion & Rahaman (2020) and the 2016 PARTHENOS White Paper (Alliez et al., 2016) for 3D web viewer features.

Feature	Smithsonian Voyager (Explorer & Story)	ATON	3DHOP	Kompakkt	Virtual Interiors
Zoom	✓	✓	✓	✓	✓
Rotation	✓	✓	✓	✓	✓
Walk around/through the 3D model	✓	✓	✗	✗	✓
Add, Remove or move parts of the 3D model	✗	✗	✗	✗	✓
Wireframe view	✓	✗	✗	✗	✓
Texture view	✓	✓	✓	✓	✓
Take screenshot	✓	✓	✓	✗	✗
Annotation of text	✓	✓	✓	✓	✓
Annotation of image	✓	✓	✓	✓	✗
Change field of view	✓	✓	✓	✗	✓
Measure the 3D model	✓	✓	✓	✗	✗
Download of the 3D model	✓	✗	✗	✗	✗
Timeline	✗	✓[6]	✗	✗	✗
DOI (digital object identifier)	GUID	✗	✗	GUID	GUID
Dynamic lightning	✓	✓	✓	✗	✓
Cut-through sections	✓	✗	✓	✗	✗
Export the cut-through profile	✗	✗	✗	✗	✗
Layers for enhanced visibility and inspection	✗	✓	✓	✗	✓
Toggle Alternative Hypotheses	✗	✗	✗	✗	✓
Certainty Index	✗	✗	✗	✗	✓

Table 2 Comparison of features from different web viewers.

[6] Feature available on project derived from ATON: EMviq.

2.3.3 Recommendations

As seen in the previous sections, there are many web viewers available for the viewing and editing of 3D objects on the web. For the PURE3D project, it is important that the viewer be open source and available with examples and documentation, so that the initial workload time to installation and configuration may be as minimal as possible. While ATON and Voyager has good documentation and some appealing features for model inspection, Virtual Interiors offers unique features for addressing hypothesis and certainty in a 3D (re)construction. However, documentation for Virtual Interiors is lacking as the project is still in development phases and have not yet released the code for open source use. It is recommended that an open dialogue with Virtual Interiors take place to get pre-access to the code and documentation as well as to discuss the possibility to customize and expand its features for the purposes of PURE3D.

2.4 Existing Repository Systems

One of the key deliverables of the PURE3D project is the development of a scholarly environment to present 3D scholarly editions as well as archive, preserve and make data FAIR (in collaboration with DANS, who has the expertise in this area). Therefore, it is useful to review some state-of-the-art repository systems that can serve as a starting point for PURE3D. However, a quick search on Google reveals a plethora of potentially relevant systems, all of which is impractical to explore in full detail. As a result, an approach was adopted whereby the key characteristics of each notable system was extracted and used to identify a shortlist of systems which can be further explored in later stages of the design process.

To ensure that the search results are not restricted to academic repository systems, Google was used as the main search engine, and the main search terms were: *content management systems* (CMS); *institutional repositories*; and *digital asset management (DAM) systems*; Repositories specifically used in digital humanities and digital cultural heritage were also searched, but in all cases, the focus was on systems that are open-source and can store different types of files. The result was a total of 21 repository systems; however, due to the reasons summarized below, a shortlist of three repository systems were identified: DSpace, Fedora and Dataverse. A more detailed comparison of the 21 repository systems can be found in Appendix B.

2.4.1 Content Management System (CMSs)

Content management systems (CMSs) generally refer to systems for managing web content; some popular examples include WordPress, Drupal, Joomla and SilverStripe. Since their main purpose is for authoring websites instead of archiving and enabling FAIR data, they are excluded in this analysis. However, it is envisaged that a CMS may eventually be required as part of the PURE3D infrastructure, and some of the interesting features they can provide include community participation and publishing workflows.

2.4.2 Institutional Repositories (IRs)

Unlike CMSs, institutional repositories are designed to support the storage and sharing of FAIR data (of any kind). The main examples are DSPace, Fedora, Dataverse, Invenio, CKAN, EPrints and Open Journal System.

DSpace (https://duraspace.org/dspace/) is one of the most well-known open-source software for digital repositories, with roughly 3000 known instances listed on its website. DSpace is designed to be a monolithic, turn-key solution that includes both a front-end as well as a back-end. As a result, DSpace is intended to be very easy to deploy and maintain, provided that it is used as is with no substantial changes to the underlying code. For example, Texas A&M University reported significant challenges in using DSpace due to the number of bespoke tools developed on top of it, all of which required modifications after every upgrade to DSpace (Sewell et al., 2019). Another limitation is that DSpace only supports a flat metadata structure and lacks a versioning system.

Fedora (https://duraspace.org/fedora/) is another well-known open-source repository with roughly 300 known user organisations as listed on its website. In many ways, Fedora can be considered as the counterpart of DSpace in that it only provides the basic features of a repository system and is designed to be incorporated into other systems via an API. Due to its barebones nature, Fedora is generally considered to be hard to use and requires a dedicated software team to set up and maintain (e.g., Teperek and Dunning, 2020). However, Fedora conforms to the Linked Data Platform standards, and larger frameworks have been developed on top of it, notably Islandora (https://islandora.ca/) or Samvera (https://samvera.org/). The former (i.e., Islandora) provides a Drupal front-end (and other middleware) on top of Fedora, while Samvera provides a set of Ruby-on-Rails components on top of Fedora. An example usage of Samvera is MorphoSource, which is a repository of 3D models for biological specimen objects and cultural heritage objects.

Dataverse (https://dataverse.org/) is perhaps not as popular as Fedora or DSpace with only around 70 known instances. However, it is of particular relevance to PURE3D as it is also used by DANS and can therefore assure compatibility with existing national research infrastructures. Furthermore, it is explicitly designed to support academic research, including making data FAIR, generating citations and collecting usage statistics. Compared with Fedora and DSpace, Dataverse lies between them in terms of flexibility and the functionality it inherently provides. Like Fedora, Dataverse also provides APIs for integration with custom system components, but like DSpace, Dataverse contains more in-built features such as for searching the repository and for controlling user access. However, Dataverse has a smaller community than Fedora and DSpace and offers fewer extensions.

As mentioned previously, DSpace, Fedora and Dataverse are the three candidate repository systems that will be investigated further for use in the PURE3D project. Other potential candidates, notably Invenio, CKAN, EPrints and Open Journal System are excluded from the shortlist for various reasons. Firstly, while Invenio (https://inveniosoftware.org/) is built on the open-access repository Zenodo and adopts modern web standards for full integration with customised systems, it seems to have a smaller community and is not as well-documented. Furthermore, CKAN (https://ckan.org/), while adopted by various government organisations around the world (e.g., in Canada, Australia and Switzerland) as their public data management system, is excluded as it is mainly designed to support open-access data with limited access controls. Similarly, since EPrints (https://www.eprints.org/) and Open Journal Systems (https://pkp.sfu.ca/ojs/) are intended specifically for managing publications, they are excluded from this analysis.

2.4.3 Digital Asset Management (DAM) Systems

As its name suggests, digital asset management systems are designed for managing all kinds of digital assets; examples include Phraseanet, ResourceSpace and Nuxeo. In general, these systems are developed by commercial organisations to manage private data and are therefore less FAIR than institutional repositories. For example, they generally don't support interoperability with other systems. On the other hand, they include more features that allow users to work with their assets, such as annotating them, analysing their popularity, and publishing them on social media. However, they generally seem to have a smaller community of developers, and they are sometimes not completely open source. Many vendors only release a simplified version of the system as open source while their complete system remains proprietary. This means that there is significantly increased risk of becoming dependent on the vendor if such DAM systems are adopted for PURE3D.

2.4.4 Repositories for Digital Humanities

Apart from the generic repository systems presented above, systems specifically designed for digital humanities and digital cultural heritage were also searched. The main examples are Arches, Mukurtu, Omeka and Scalar. GAMS is another repository that is developed in Austria, but it doesn't seem to be used elsewhere nor contain any notable features that are missing in other systems, so it was excluded from consideration. Other specific systems that have been excluded are Fulcrum, Manifold and RavenSpace; these systems are designed for publishing texts with accompanying multimedia content, which is not the aim of PURE3D.

In general, these repositories for digital humanities are less FAIR than institutional repositories and have less advanced features than commercial digital asset management systems. However, they are designed to include some other domain-specific features such as the use of controlled vocabularies in the metadata. Furthermore, they generally also provide support for community participation, such that users can, for example, add their own stories and/or annotations to the digital assets. However, these repositories typically lack a developers' community and developers' documentation. As a result, while these systems contain some useful features and can serve as useful references, it is envisaged that none of these systems will be incorporated into the PURE3D infrastructure.

2.4.5 Recommendations

Since one of the key requirements of PURE3D is to ensure that 3D scholarly editions are FAIR, it is recommended that institutional repository systems be used for storing and retrieving 3D scholarly editions. Of the main examples of institutional repositories, all of which can (or can be extended to) support any file type and flexible metadata schemas, it may be useful to focus on DSpace, Fedora and Dataverse due to the reasons presented above.

In particular, given that many of the requirements of PURE3D have yet to be identified, a Fedora-based solution seems to be the most promising. Since Fedora only provides the bare-bones of a repository, it allows us to incrementally add any features as they are discovered. At the same time, the large Fedora community implies that many solutions already exist for implementing common repository functions, such as for searching the repository. Indeed, it may be useful to start the development of PURE3D using the Samvera framework, which may be preferable over Islandora. Islandora is designed to only be extended using Drupal extensions, which may be less flexible than the use of Ruby-on-Rails gems by Samvera.

3 User Requirements

For the month of March 2021, three pilot partner sessions were organized in which the lead partners were asked to present on either their existing digital project (Erfgoed Leiden en Omstreken; 4D Research Lab @UvA) or an intended digital project (Gemeente Maastricht; Museum Van Bommel van Dam; Nederlands Mijnmuseum). After the presentations, there was a discussion between the Core PURE3D team and the pilot partners whereby questions could be addressed to either party and discussion prompts were posed to the partners.

Based on these presentations and the subsequent discussions, some reoccurring concerns and themes were identified. These included topics regarding intended end-users and audience, the potential of digital storytelling and conceptualizations of 3D Scholarly Editions.

3.1.1 Audience

End-users of a 3DSE may include not only academic scholars but also the general public. This is reiterated by some pilot partners who stressed that public audiences are also a high priority stakeholder for their digital projects. Therefore, the final UX of PURE3D should accommodate both target audiences – the scholarly as well as the general. This also goes for the level of detail that data and annotations will go into – depending on the project and the intended audience of the 3D data publication. Thus, the challenge for PURE3D is to determine conventions for annotations and a design interface that is easily accessible for all demographics and for people with lower technical abilities. To get a user-friendly final product, we will need to perform varied surveys, tests, and control group evaluations alongside the development process.

3.1.2 Storytelling

Storytelling was another re-occurring theme across all sessions. Storytelling includes both the over-arching narrative(s) of the project author as well as the ability for users to be able to contribute and share their own stories about an object or place. The point was made in these sessions that the public values history and cultural heritage more when they are allowed to participate and contribute their own experiences to the ‘official’ narrative. Thus, the system should enable engagement from users in the form of community participation so that they can give additional meaning to the facsimile of the digital content and, in so doing, the associated real-world objects.

Understanding different storytelling modalities are also important considerations for development of the infrastructure. Will the platform be restricted to an annotated hotspot connected to a specific point on an object? Will the narratives be built and guided by the author(s) in a logical order? Or can it (additionally) be freely discoverable by the end-user? How might animation contribute to storytelling or facilitating a contextualized understanding of the content?

3.1.3 3DSE Conceptualization

One pilot partner highlighted the potential of a 3DSE for publishing a research project at various stages in the research process. A kind of versioning system of a 3D project in which a published model can be designated as a 'work in progress' or 'complete' to the author's knowledge and abilities. From here, the author can update the model himself based on feedback and/or new information coming to light, keeping a record or version of previous iterations stored within the infrastructure. The overall benefit of this system is a way to contribute to the body of knowledge on a subject or topic and leave a legacy that can be expounded on by future researchers when new information is produced.

3.1.4 Recommendations

- *User Interface and annotations should be designed in a way that is engaging and intuitive for both the general audience and the scholarly research community.*
- *In early stages of development, test the UI with focus groups and control groups*
- *Search for an optional web viewer feature in which end-users contribute to the 3D content through storytelling of their own experiences with places, people, objects.*
- *Explore different modalities of storytelling, narratives, and annotation*
- *Functionality for authors to signify whether their project is in certain stages of research and whether they are open for community input.*
- *Functionality to allow authors to make their 3D assets re-usable if they are willing and able to do so.*
- *Advocate the 3DSE as a staging ground for direct communication between researchers and the public–without being mediated through the press, museums or other educational platforms.*

3.2 Survey Responses

3.2.1 Introduction

Between late May and late July 2021, PURE3D collected responses to an online survey regarding user requirements for 3D Web Infrastructures using Qualtrics XM. The survey asked respondents to provide their input on their profession as 3D content creators and/or managers in addition to collecting opinions on web viewer features and preservation/publication standards. A final portion of the survey asked respondents to answer questions about a specific digital project they were involved with. While a little more than 90 responses were collected by the system, only about 48 were all or mostly completed. Of the 48 respondents, 24 choose to provide information about their own 3D project. Graphics for these responses have been generated and included in Appendix C of this report. A more detailed report on the survey data can be accessed in the "PURE3D Survey on 3D Web Infrastructures Final Report" that will also be released in 2021.

3.2.2 Survey Results

Based on these preliminary results of the survey we can get a sense of what is important to 3D content creators and managers. Before preliminary recommendations are laid out, we need to understand the professional background and work area from the majority of the respondents. A high number of respondents are coming from the University/Higher Education sector (54%) with the second highest sector being from a Research Lab or Institute (15%) [Q2 on the survey report]. The types of 3D content the respondents are working with include: photogrammetry (87.5%), computer graphic reconstructions (69%), 3D Scans (65%), point cloud data (54%), terrestrial laser scanning (46%), aerial scanning (35%) and BIM (21%). [Q3]. The predominant file format they are using is .obj (85%) with .stl (42%), .blend (35%) and .fbx (33%). .glTF (29%) and .glb (27%) were less common, however this may be because .glTF and .glb are newer open file formats designed for 3D web handling [Q4].

Survey Responses	Essential	Fairly Important	Neutral
Viewing Device			
Desktop/Laptops	✓		
Tablets	✓		
Mobile Devices	✓		
VR/AR		✓	
Viewer Features			
Measurement Tool	✓		
PBR Materials	✓		
Enable/Disable parts of the scene	✓		
Integrated Screenshot Capability	✓		
Cross-Section Tool		✓	
Timeline		✓	
Advanced Lighting Capabilities		✓	
Animations		✓	
Particle Systems			✓
Ambient Sound			✓
Annotations			
Assigned a UID	✓		
End User can add annotations	✓		
By Object	✓		
By Region	✓		
Linkable to external resources	✓		
Multiple Contributors can add annotations		✓	
Linkable to other Objects in the Scene		✓	
Linkable to another annotation in the scene		✓	
By Point/Vertex			✓
Numerically organized through one or more guided tours			✓

End-User Capabilities			
Create profile to comment or download content	✓		
Download content if permitted by author(s)	✓		
Like or Follow Projects	✓		
Comments reported as inappropriate or offensive	✓		
Can download original resolution version	✓		
Can download reduced resolution version	✓		
Can download a file with all the multi-media annotations	✓		
Can access only by personal request	✓		
Comment Freely and Publicly		✓	
Send Private messages to the author		✓	
Comments deleted by the author		✓	
Can download after set embargo period		✓	
Platform/Infrastructure			
Create DOI to make content searchable across the web	✓		
Have refined search function	✓		
Provide licensing information	✓		
Include information on how to cite the project, objects and annotations	✓		
Should keep and maintain models for however long the platform is being support	✓		
Allow search engines to harvest data from the platform		✓	
Should keep and maintain models for more than 10 years		✓	

Table 3 Survey indications for features and functionalities

Additional Responses regarding long-term preservation, recognition and peer-review:

1. Users would include in a project's funding module the cost of perpetual care and long-term preservation. [Q15]
2. Users would, with either personal funding or project funding, be willing to pay for perpetual care of the models with either a single upfront fee or a yearly subscription model. [Q16]
3. For users who do not wish to pay, they are willing to update their 3D content to future standards when prompted. [Q16]

4. Over 50% of respondents say that organizations are recognizing and rewarding 3D scholarship as atypical outputs. [Q17]
5. There is a slight tendency for respondents who believe that projects should be peer-reviewed before being published on the platform. Suggestions from individuals include a hybrid approach in which some models or projects can be submitted for peer-review but that this shouldn't be a limiting condition for publication on the platform. [Q18]

3.2.3 Recommendations

While survey results indicate what is generally preferred by 3D Cultural Heritage experts, there is some amount of nuance that is missing. By conducting follow-up interviews and focus groups of diverse stakeholders, we will have the opportunity to tease out these nuances. In that sense, the survey was a good starting point to structure our objectives for these upcoming focus groups and interviews. The recommendation is to not use the survey data as a final 'wish list' for the PURE3D Infrastructure, but rather to utilize it in combination with the environment scan, interviews and stakeholder focus groups. When we have sufficiently collected this data, we can begin designing the infrastructure architecture.

4 Guidelines/Recommendations for developing the PURE3D Infrastructure

4.1 Entity Model of 3D Scholarly Edition

4.1.1 Initial Proposal

Since 3D scholarly editions form the core of PURE3D, it may be useful to give 3D scholarly editions a more precise definition and description that can later be used to guide the detailed design and implementation of the PURE3D architecture. This section focuses in particular on the high-level entities that constitute a 3D scholarly edition, thus low-level design details, such as the choice of metadata descriptors, are not considered at this stage. Furthermore, it should be noted that the model presented in this section serves only as an initial proposal for further discussion.

Conceptually, a 3D scholarly edition can be thought of as comprising "the primary text (in this case the 3D model) along with its accompanying annotation and apparatus" (Papadopoulos & Schreibman, 2019). Thus, as shown at the top of Figure 13, a 3D scholarly edition may be modelled in PURE3D as containing one or more 3D objects that together constitute a the "text" as well as a critical apparatus that provides additional information for understanding the 3D models. Although not mentioned explicitly in its definition, a 3D scholarly edition is also modelled to contain an initial view which specifies the initial conditions under which the 3D models should be displayed on screen, such as the position and angle of the camera as well as the lighting conditions.

Figure 13 largely follows the notation used in UML (Unified Modeling Language) class diagrams; each rectangle represents a high-level entity while each arrow represents a relation between the connected entities. The arrows are given different shapes or labels to denote specific types of relations, and the ends of an arrow may be associated with a number to denote its cardinality. For example, the arrow pointing from "Edition" to "3D Object" with cardinality "1..*" indicates that a 3D scholarly edition is composed of 1 or more 3D objects. In fact, Figure 13 also shows that an explicit distinction is made between 3D models, which may be re-used in multiple editions, and 3D objects, which are instances of 3D models at, for example, the appropriate locations and orientation.

As an initial proposal, the critical apparatus of 3D scholarly editions is modelled to contain a collection of four different types of entities:

- Annotations, which redirect the "reader" to further information about a specific region in the "text". They are modelled to contain a content, which may be linked to and/or embedded with other resources, as well as a marker, which indicates the specific region of interest. By embedding external resources, i.e., resources that exist outside of the 3D scholarly edition, these annotations need not be text-based only; they can also be image-based or audio-based provided the corresponding file formats are supported by the 3D web viewer.

- Overlays, which are instances of other resources that enrich a 3D scholarly edition by being overlaid on top of its 3D models. A 3D reconstruction of a building, for example, may be overlaid with the photo or plan on which it is based. In many ways, overlays are similar to annotations. As with annotations, overlays can be based on any type of resource (e.g., image, audio, 3D models and even other 3D scholarly editions etc.) provided it is supported by the 3D web viewer. Furthermore, overlays may include caption with further explanation on what they represent. However, the different between annotations and overlays is that annotations point to extra "text" in the margins while overlays are material overlaying the original "text".
- Qualifiers, which add qualifying information to one or more 3D models. A 3D model of a building may, for example, be qualified with the time period during which the building existed as well as the level of uncertainty in the reconstruction process. The evidence for these qualifiers is provided by links to zero or more annotations or overlays.
- Highlights, which are pre-defined views of a 3D scholarly edition. These highlights can be linked together to form tours, which allow readers to follow a pre-defined narrative through all the information captured by the apparatus.

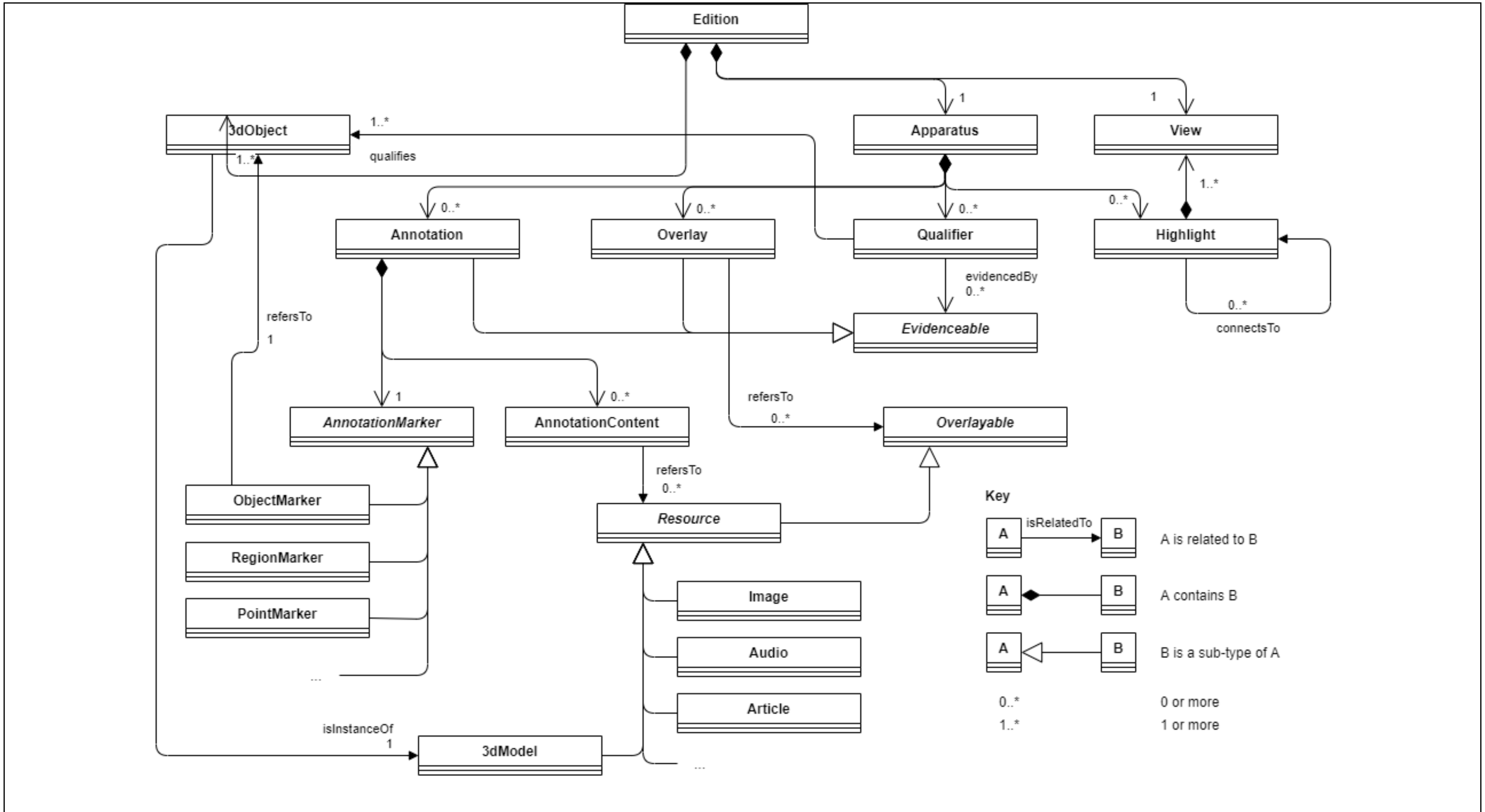


Figure 13: Initial high-level model of 3D scholarly editions.

4.1.2 Implications and Limitations of the Model

The model presented in Figure 13 is only an initial proposal of how 3D scholarly editions may be represented in the PURE3D infrastructure. It is likely that as new requirements are discovered certain elements of the model may need revision. For example, one notable feature that is not explicitly captured by the model is a timeline, which is useful to show how, for example, an archaeological site has gradually evolved. While such a timeline can be easily inferred from the temporal qualifiers attached to the 3D models, it may be more appropriate to model time as a separate entity. On the other hand, by incorporating time into qualifiers, it facilitates the assignment of different levels of uncertainty to the 3D models at different time periods.

Furthermore, under this model of a 3D scholarly edition, elements of an apparatus cannot themselves contain an apparatus. For example, one key feature of Scalar (https://scalar.me/anvc/scalar/) is that annotations can themselves be annotated, but under the proposed model of 3D scholarly editions, only 3D scholarly editions can be annotated. This means, for example, that it would not be possible to add annotations to overlays or other annotations, nor can annotations be qualified. However, since elements of an apparatus can be linked to external resources, i.e., resources that exist outside of the 3D scholarly edition, one method to an apparatus to the apparatus of a 3D scholarly is to add support for other kinds of scholarly editions. In this way, the apparatus of a 3D scholarly edition can itself become a scholarly edition.

Another design consideration that should be considered is whether annotations, overlays and qualifiers are sufficiently different to be treated as separate entities (e.g., get assigned a DOI and stored as separate files in the repository). Qualifiers can also be captured using annotations while overlays can be considered as simply an alternative means to annotate 3D models. On other hand, not all annotations may be qualifiers or can be overlaid, thus it may be useful in subsequent design iterations to more carefully distinguish the different types of elements that constitute an apparatus. This will also aid the creators of 3D scholarly editions in creating the apparatus.

Regarding the qualifiers, another limitation to the model is that they can only be assigned to whole 3D models, not parts of them; this can be a problem when, for example, modelling partially destructed objects. Furthermore, alternative hypotheses are also not explicitly incorporated into the model. However, possible workarounds to these limitations may be to, respectively, divide a single model of an object into multiple sub-models and to add alternative hypotheses as overlays. Instead of dividing an object into multiple sub-models, an alternative is to adopt the approach of annotations, with each qualifier assigned an area of concern. However, this approach may not work well for temporal qualifiers, such as to display the changes to different parts of a building over time. Furthermore, an annotation area may lack the precision that sub-models can offer.

4.2 Component Architecture for PURE3D

4.2.1 Base Architecture

The PURE3D infrastructure combines and extends the functionalities of both existing 3D web viewers and existing digital repositories, thus its starting component architecture is a combination of the two system architectures shown in Figure 14 for 3D web viewers (left) and digital repositories (right). As expected for 3D web viewers, their key component is the GUI front-end, which is generally built on top of a JavaScript-based 3D engine such as Babylon.js and Three.js. For more complex 3D web viewers that support the processing of 3D models, such as to incorporate annotations or to reduce the file size, the front-end may also be connected to a back-end component. In the case of both ATON and Voyager, this back-end component is also programmed using JavaScript, and it connects the GUI front-end to a filesystem where the 3D models and associated resources are stored and retrieved.

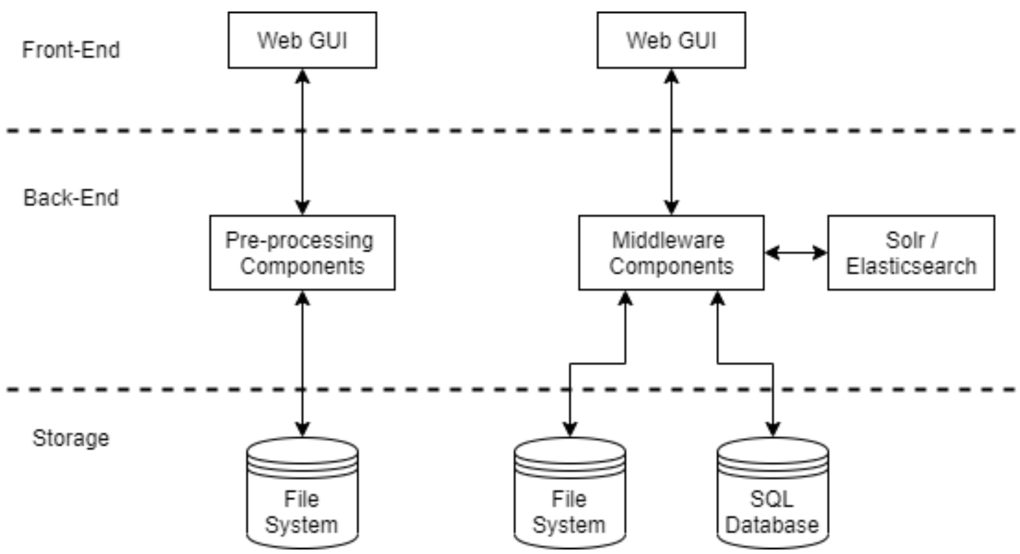


Figure 14: High-level component architecture of 3D web viewers (left) and repository systems (right).

Like 3D web viewers, digital repositories also contain a web GUI to allow users to, e.g., upload, browse and download resources as well as a custom middleware layer to process user requests and to communicate with the filesystem (Figure 14). Furthermore, digital repositories typically store metadata in a relational (i.e., SQL) database and use Solr or Elasticsearch as the search engine for indexing and searching resources. However, it is useful to note that unlike 3D web viewers that are generally JavaScript-based, digital repositories are implemented using a variety of languages and technologies, including Java (for DSpace and Dataverse), Ruby on Rails (for Samvera) and Python and Drupal (for Islandora).

4.2.2 Integration Considerations

One of the main considerations when integrating a 3D web viewer and a repository system into the PURE3D infrastructure is the workflows and use cases that it should support. For uploading and viewing 3D scholarly editions, the digital repository systems can be largely reused without much adaptation. The only requirement is that the digital repository should be adjusted to recognize the file format for 3D scholarly editions and re-direct the user to the 3D web viewer.

However, complications arise because the PURE3D infrastructure should also support the creating and editing of 3D scholarly editions. In order for the 3D web viewer to create and edit 3D scholarly editions, it should be able to, for example:

- Connect to the repository's authentication and authorization mechanism to ensure that the user has the correct permissions to edit/create 3D scholarly editions.
- Upload 3D scholarly editions to the repository with the appropriate metadata, URI, etc. If the 3D models and other resources are not already in the system, the 3D viewer needs to be able to upload them as well.
- Ensure the repository's search engine is updated to reflect any changes to the 3D scholarly edition.
- Make appropriate use of any versioning and reviewing system provided by the repository.

In fact, if Figure 13 is adopted as the model for 3D scholarly editions, then the following questions must also be addressed:

- How can a user create a scene from multiple 3D models?
- How can overlays be added onto a scene for display in the 3D web viewer?

4.2.3 Storage Considerations

Both Voyager and ATON represent scenes as a JSON file, thus it is envisaged that PURE3D will also use JSON to represent 3D scholarly editions in the front-end. However, compared to other typical resources in a repository, one key feature of 3D scholarly editions is that they contain many references to other resources, including 3D models, images and textual articles. This gives rise to the possibility of storing 3D scholarly editions as relations in a database as opposed to (or as well as) storing them as JSON files in the filesystem. This will introduce additional complexities to the design of the system, as the relations will need to be converted to JSON for the 3D web viewer, but this may also allow some additional features to be implemented.

For example, by storing 3D scholarly editions as relations, the system would be able to more effectively answer queries about them. These queries can include finding all 3D scholarly editions that refer to a particular image and determining all the references shared between multiple different editions. Such an approach to storing 3D scholarly editions may also facilitate the management of different versions of resources. A 3D model may, for example, be updated or even deleted at any time, after which the system should take the necessary steps to mitigate the impact on any affected 3D scholarly editions.

4.3 Next Steps

The recommendation for the next steps of PURE3D includes the minimum viable product (MVP) strategy. Designed to get a simple basic product to market in a short time as possible, it allows the examination of the feasibility of the product and helps to determine which features should be added in the next iteration of the product development.

It is a user-focused design approach which gathers valuable feedback constantly to provide an improved product at each iteration. The iterative development follows a build-measure-learn process. The first step to start the MVP development is to identify and prioritize PURE3D features, which can be done on the focus groups and interviews.

After features identification and specification, user stories may be built, to define the priority of each feature and when in the development it should be added to the software. A backlog with all the details of each feature is a useful tool, as all team members may keep track on what needs to be done and how much work is necessary to achieve it.

As for the remaining of the project development, the list below covers the main objectives to be achieved regarding its infrastructure:

1. Update system design:
   a. Collect/study documentation about candidate repositories/web viewers.
   b. Collect documentation for candidate repositories/web viewers.
   c. Experiment with candidate repositories/web viewers.
   d. Choose framework for web viewer.
   e. Choose repository system.
   f. Update architecture specification
      i. Update scholarly editions entity model.

2. Proof of concept:
   a. Install and deploy the repository system on CLARIAH.
   b. Install and deploy the web viewer on CLARIAH.
   c. Integrate repository and web viewer APIs.
   d. PURE3D prototype.
      i. Start with minimum viable product.
      ii. Incrementally add features to prototype.

5 References

Alliez, P., Bergerot, L., Bernard, J.-F., Boust, C., Bruseker, G., Carboni, N., Chayani, M., Dellepiane, M., Dell'unto, N., Dutailly, B., Gautier, H., Guidi, G., Guillem, A., Jofres, A., Laroche, F., Manuel, A., Manzetti, M. C., Michel, A., Pamart, A., … Tournon-Valiente, S. (2017). Digital 3D Objects in Arts and Humanities: Challenges of Creation, interoperability and preservation. White Paper: A result of the PARTHENOS Workshop held in Bordeaux at Maison des Sciences de l'Homme d'Aquitaine and at Archaeovision Lab (France), November 30th – December 2nd, 2016. [Technical Report] European Commision; Horizon H2020 Projects.

Archaeology Data Service (2020, June 16). *Guides to Good Practice*. Retrieved from Archaeology Data Service / Digital Antiquity: https://guides.archaeologydataservice.ac.uk/g2gp/3d_2-3

Boutsi, A.-M., Ioannidis , C., & Solie, S. (2019). An Integrated Approach to 3D Web Visualization of Cultural Heritage Heterogeneous Datasets. *Remote Sensing 11(2508),* 1–26., doi: 10.3390/rs11212508

Champion, E. (2016). The Missing Scholarship Behind Virtual Heritage Infrastructures. In *Proceedings of The 14th EUROGRAPHICS Workshop on Graphics and Cultural Heritage (GCH '16)* (pp.57–65). Goslar, Germany: Eurographics Association.

Champion, E., & Rahaman, H. (2020). Survey of 3D Digital Heritage Repositories and Platforms. *Virtual Archaeology Review, 11*, 1–15. doi: 10.4995/var.2020.13226

Clarke, M. (2015). The Digital Dilemma: Preservation and the Digital Archaeological Record. *Advances in Archaeological Practice, 3(4),* 313–330. doi: 10.7183/2326-3768.3.4.313

CNR ISPC. (2021, June 07). *ATON: Open-source Web3D framework by CNR ISPC*. Retrieved from ATON: http://osiris.itabc.cnr.it/aton/

Eide, Ø., Gerrit Wieners, J., Schubert, Z., & Türkoglu, E. (2019). The intangibility of tangible objects: re-telling artefact stories through spatial multimedia annotations and 3D objects. *25th ICOM General Conference: Museums as Cultural Hubs: The Future of Tradition. Kyoto 1-7 September, 2019* (pp. 1–14). doi:10.5281/zenodo.3878966

Europeana Network Association Members Council. (2019). *3D content in Europeana task force*. Retrieved from https://pro-beta.europeana.eu/files/Europeana_Professional/Europeana_Network/Europeana_Network_Task_Forces/Final_reports/3D-TF-final%20report.pdf

Evans, A., Agenjo, J., & Blat, J. (2017). A pipeline for the creation of progressively rendered web 3D scenes. *Multimedia Tools and Applications, 77*, 20355–20383. doi: 10.1007/s11042-017-5463-6

Fanini, B., Ferdani, D., & Demetrescu, E. (2021). Temporal Lensing: An Interactive and Scalable Technique for Web3D/WebXR Applications in Cultural Heritage. *Heritage, 4*, 710–724. doi:10.3390/heritage4020040

Giovannini, E. (2020). Workflow for an evidence-based virtual reconstruction: the marbles of the ciborium of the early medieval Monte Sorbo church. *ISPRS - International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences, XLIII-B2-2020* (pp. 1395–1402). doi:10.5194/isprs-archives-XLIII-B2-2020-1395-2020

Greenop , K., & Barton, J. (2014, February 12). *Scan, save, and archive: how to protect our digital cultural heritage*. Retrieved from The Conversation: https://theconversation.com/scan-save-and-archive-how-to-protect-our-digital-cultural-heritage-22160

Hansen, H. J., & Fernie, K. (2010). CARARE: Connecting Archaeology and Architecture in Europeana. In M. Ioannides (Ed.), *Digital Heritage* (Vol. 6436), (pp. 450–462). Springer-Verlag: Berlin, Heidelberg. DOI: 10.1007/978-3-642-16873-4_36

Hardesty, J., Johnson, J., Wittenberg, J., Hall, N., Cook, M., Lischer-Katz, Z., Xie, Z., & McDonald, R. (2020). 3D Data Repository Features, Best Practices, and Implications for Preservation Models: Findings from a National Forum. *College & Research Libraries,* 789–807. DOI: 10.5860/crl.81.5.789

Hauck, O., & Kuroczynski, P. (2015). Cultural Heritage Markup Language – Designing a Domain Ontology for Digital Reconstructions. *Proceedings of the 2nd International Conference on Virtual Archaeology, Hermitage Museum, St. Petersburg, Russia,* 250–255.

Huurdeman, H. & Piccoli, C. (2021). 3D Reconstruction as Research Hubs: Geospatial Interfaces for Real-Time Data Exploration of Seventeenth-Century Amsterdam Domestic Interiors, *Open Archaeology, 7,* 314–336.

IANUS. (2020, June 16). *IT-Empfehlungen für Altertumswissenschaften*. Retrieved from IT-Empfehlungen Für den nachhaltigen Umgang mit digitalen Daten in den Altertumswissenschaften: https://www.ianus-fdz.de/it-empfehlungen/3d

Bendicho, V.M. L.-M. (2013). International Guidelines for Virtual Archaeology: The Seville Principles. In: C. Corsi, B. Slapsak, F. Vermeulen (Eds.) *Good Practice in Archaeological Diagnostics. Natural Science in Archaoelogy,* (pp. 269–283). Cham, Switzerland: Springer. DOI: 10.1007/978-3-319-01784-6_16

Jacobsen, A., de Miranda Azevedo, R., Juty, N., Batista, D., Coles, S., Cornet, R.,... & Schultes, E. (2020). FAIR principles: Interpretations and implementation considerations. *Data Intelligence, 2*, 10–29. doi: 10.1162/dint_r_00024

Khronos Group. (2021, June 10). *OpenGL ES Overview*. Retrieved from Khronos: https://www.khronos.org/opengles/

Khronos Group. (2021, June 10). *WebGL Overview*. Retrieved from Khronos: https://www.khronos.org/webgl/

Koller, D., Frischer, B., & Humphreys, G. (2009). Research challenges for digital archives of 3D cultural heritage models. *Journal on Computing and Cultural Heritage, 2*(3), 1–17. doi:10.1145/1658346.1658347

Kubik, T., & Kwiecień, A. (2021). Resolving Dilemmas Arising during Design and Implementation of Digital Repository of Heterogenic Scientific Resources. *Applied Sciences, 11,* 1–19. DOI: 10.3390/app11010215

Kuroczynski, P. (2014). Digital Reconstruction and Virtual Research Environments – A question of documentation standards. *Proceedings of the annual conference of CIDOC 2014 in Dresden, Germany,* (pp. 1–9).

Kuroczynski, P., Hauck, O., & Dworak, D. (2016). 3D Models on Triple Paths – New Pathways for Documenting and Visualizing Virtual Reconstructions. In S. Münster, M. Pfarr-Harfst, P. Kuroczynski, & M. Ioannides (Eds.) 3D Research Challenges in Cultural Heritage II, (pp. 149–172). Basel: Springer International Publishing

McHenry, K., & Bajcsy, P. (2008). *An Overview of 3D Data Content, File Formats and Viewers*. Urbana, IL: Image Spatial Data Analysis Group - National Center for Supercomputing Applications. Retrieved from https://www.archives.gov/files/applied-research/ncsa/8-an-overview-of-3d-data-content-file-formats-and-viewers.pdf

Mwalongo, F., Krone, M., Reina, G., & Ertl, T. (2016). State-of-the-Art Report in Web-based Visualization. *Computer Graphics Forum*, 35(3), 553–575. doi:10.1111/cgf.12929

Nabil, M., Chatzi, E., Mayo, S. B., Rizvic, S., Karygiannis, J., Sideris, T., Hermon, S., & Wallergård, M. (2011). Deliverable Report: Methodologies, Compatibility & Re-usability (V-Must.net D 2.4; p. 25). *Center for Documentation of Cultural & Natural Heritage (CULTNAT) VirtualWare*, ETF, IME, CREF-Cyl, Ulund

Nishanbaev, I. (2020). A web repository for geo-located 3D digital cultural heritage models. *Digital Applications in Archaeology and Cultural Heritage, 16,* 1–9. doi: 10.1016/j.daach.2020.e00139

Papadopoulos, C., & Schreibman, S. (2019). Towards 3D Scholarly Editions: The Battle of Mount Street Bridge. *DHQ: Digital Humanities Quarterly, 13(1)*, 1–26.

Ponchio, F., Potenziani, M. Dellepiane, M., Callieri, M. & Scopigno, R. (2016). ARIADNE Visual Media Service: Easy Web Publishing of Advanced Visual Media. *Proceedings of the CAA 2015 43rd Annual International Conference on Computer Applications and Quantitative Methods in Archaeology, Siena, Italy,* (pp. 433–441).

Potenziani, M., Callieri, M., Dellepiane, M., & Scopigno, R. (2018). *Publishing and Consuming 3D Content on the Web: A Survey*. Boston/Delft: Now Foundations and Trends. doi:10.1561/0600000083

Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Ponchio, F., & Scopigno, R. (2015). 3DHOP: 3D Heritage Online Presenter. *Computer & Graphics, 52,* 129-141. doi: 10.1016/j.cag.2015.07.001

Scopigno, R., Callieri, M., Dellepiane, M., Ponchio, F., & Potenziani, M. (2017). Delivering and Using 3D Models on the Web: Are We Ready? *Virtual Archaeology Review, 8(17),* 1–9. DOI: 10.4995/var.2017.6405

Sewell R. R., Potvin S., Melgoza P., Creel J. S., Huff J. T., Bailey G. T., Bondurant J., Buckner S., duPlessis A. R., Furubotten L., Mosbo Ballestro J. A., Muise I. W. & Wright B. J., (2019). When a Repository Is Not Enough: Redesigning a Digital Ecosystem to Serve Scholarly Communication. *Journal of Librarianship and Scholarly Communication 7(1)*. doi: 10.7710/2162-3309.2225

Shneiderman, B. (2002). Promoting universal usability with multi-layer interface design. *ACM SIGCAPH Computers and the Physically Handicapped, 73–74*, 1–8. DOI: 10.1145/960201.957206.

Sketchfab. (2019, August). *Sketchfab Cultural Heritage User Survey 2019 Results*. Retrieved from Google Docs: https://docs.google.com/presentation/d/1avExQtbfl6vDCFyo5VgSyBy638BjdDTAIhw79ClHT5A/edit#slide=id.g5dae1f95c1_0_0

Smithsonian Digitization. (2021, June 07). *Smithsonian Voyager*. Retrieved from GitHub: https://smithsonian.github.io/dpo-voyager/

Statham, N. (2019). Scientific Rigour of Online Platforms for 3D Visualization of Heritage. *Virtual Archaeology Review, 10(20),* 1–16. DOI: 10.4995/var.2019.9715

The Khronos® Group Inc. (2020, June 16). *Real-time Asset Creation Guidelines*. Retrieved from GitHub: https://github.com/KhronosGroup/3DC-Asset-Creation/blob/main/asset-creation-guidelines/RealtimeAssetCreationGuidelines.md#file-formats-and-asset-structure-summary

Visual Computing Laboratory - ISTI - CNR. (2021, June 17). *3D Heritage Online Presenter*. Retrieved from 3DHOP: https://3dhop.net/

Web 3D Consortium (2020, June 15). *X3D: The Interactive 3D Solution for the World Wide Web*. Retrieved from Web 3D Consortium: https://www.web3d.org/sites/default/files/page/X3D%20%26amp%3B%20VRML%2C%20The%20Most%20Widely%20Used%203D%20Formats/What_Is_X3D_July2017.PDF

Webb, S. & McGoohan, C. (2015). *Digital Repository of Ireland: Requirements*. National University of Ireland Maynooth. DOI: http://dx.doi.org/10.3318/DRI.2015.6

Wilkinson, M., Dumontier, M., Aalbersberg, I. et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data 3, 160018,* 1–9. DOI: doi.org/10.1038/sdata.2016.18

Zlatanova, S., Stoter, J., & Isikdag, U. (2012). Standards for Exchange and Storage of 3D Information: Challenges and Opportunities for Emergency Response. *Proceedings of the 4th International Conference on Cartography and GIS, Vol. 2, Albena, June 2012* (pp. 17-28).

6 Appendix A - File Formats

The Virtual Reality Markup Language (VRML) was released in 1995 and accepted as a standard by the Web 3D consortium. It was designed as a web standard for exchange of graphics while providing possibilities for interaction with 3D world. The format offers several texturing mechanisms and a variety of different geometries. Good visualisation performance can be obtained when using compressed binary representations (i.e., gzip), but still simple visualisations look 'too schematic'. This was one of the major reasons for rather limited use of VRML for real world projects. Considering some of the disadvantages of VRML (being not XML-based, large models result in large files, etc.), the Web 3D consortium has stopped the development of the standard after 1998 and concentrated on the XML based X3D file format (Zlatanova et al., 2012).

X3D (Extensible 3D) is a royalty-free and openly published file format standard and runtime architecture to represent and communicate 3D objects, events, and environments on the Web. The X3D suite of ISO (International Standards Organization) ratified standards provide a robust abstraction for the storage, retrieval, and playback of 3D graphics content across platforms and players including desktop applications, mobile apps, web browser plugins, and direct rendering in HTML5 pages using JavaScript libraries using WebGL. X3D scene graphs may be stored and transmitted in several standardized encodings, including Classic VRML, XML, and binary format. A common API is specified, allowing the scene graph to be queried and manipulated through multiple programming languages (Web 3D Consortium, 2020).

COLLADA (Collaborative Design Activity) is a 3D file format based on XML (Extensible Markup Language) and has a '.dae' file extension. The format is an ISO standard and under "SCEA Shared Source Licence", which can be used for commercial and non-commercial purposes. This file format can encode in-formation such as geometry, mesh geometry, boundary representation, material, texture, scene, and animation. COLLADA was built to be an interchange file format and to solve the issue of interoperability. Furthermore, it is an XML based format, hence if a 3D model is very complex, it occupies more storage and not be rendered as fast as a binary-encoded format (Nishanbaev, 2020).

OBJ format supports both plain text form and binary encoding but only the former is open source. The format has been developed by Wavefront technologies, which is now owned by Autodesk. It supports geometry, appearance, and scene; however, it does not support animation. It generates another file with an extension of '. MTL' (Material Template Library) to store the appearance of the 3D model. This format is popular for its simplicity and ease to work with (Nishanbaev, 2020).

The .3ds file format is the primary format of Autodesk's 3ds Max software. It is a binary format consisting of chunks that hold various pieces of information. Chunks contain an identification indicating what information is stored there and the offset to the next chunk. In this way, software that does not support certain rendering properties can simply ignore them. The 3ds file format supports geometry in the form of vertices/faces and parametric surfaces, textures, physical material properties, transformations, camera information, and lights (McHenry & Bajcsy, 2008).

The polygon file format (ply) was designed for the purpose of being both a flexible and portable 3D file format. The ply format has both an ASCII and a binary version. The binary version includes information to make it machine independent, specifying the types used for each value, number of bytes per type, and whether it is big or little endian. In addition, the format allows for user defined types allowing it to be extensible to the needs of future 3D data. Because of its simplicity and flexibility, the ply format is very popular in the academic and research world. The ply file format supports geometry in the form of vertices/edges/faces, vertex colors, textures and materials (McHenry & Bajcsy, 2008).

gLTF [7] (GL Transmission Format) is a 3D format and open standard by the Khronos group, which has been designed for the efficient transfer and load of 3D models. It has an aim to be versatile to represent various types of 3D assets, compact for efficient transmission, and easy to process on the client-side. It is often referred to as 'JPEG for 3D data' as many applications nowadays use this format, particularly on the Web. It supports complex 3D scenes, which can include animations, materials, etc. The core of the gLTF format is based on JSON (JavaScript Object Notation) which represents the general scene structure, cameras, and animations. However, gLTF format has two additional files linked to the core JSON file, which are files with '.bin' and 'jpg' or 'png' extensions, for geometry and texture of the 3D asset respectively (Nishanbaev, 2020).

[7] https://www.khronos.org/gltf/, date: June 15th, 2021.

7 Appendix B - Comparison of Repository Systems

Comparison Rubric

To assess and compare the 21 different repository systems, a questionnaire containing 43 questions about their features was created based on an analysis of the requirements that are implied or described in 5 source materials. These 5 source materials are based on a quick search on the requirements of infrastructures like PURE3D. Jacobsen et al. (2020) relates to the FAIR data principles while Bendicho (2013) presents the Seville Principles for virtual archaeology. Furthermore, Champion and Rahaman (2020) and Statham (2019) present two different surveys of 3D heritage infrastructures, and lastly Webb & McGoohan (2015) lay out the requirements specification for the Digital Repository of Ireland for social and cultural data. There are certainly other (and perhaps more relevant) articles that discuss the desirable features of related infrastructures, but the goal is not to compile an exhaustive list of system requirements from literature.

As presented below, the 43 questions are divided into 12 high-level categories for convenience, and each question is given a 5-point rating scale from 0 to 4; a rating of 0 represents that the system does not support the feature at all, while 4 represents full support. Where useful, a short description was added to the rating to explain what achieving it means. Furthermore, for each question, an indication was made on which rating is considered to be:

- Minimum, i.e., the bare minimum that should ideally be satisfied.
- Required, i.e., it should definitely be satisfied by PURE3D (in the ideal circumstances). In some cases, a "required" rating can coincide with a "minimum" rating.
- Desirable, i.e., it is definitely a useful feature and should be included if time allows.

Questions with a "minimum" and/or "required" rating are considered to describe an essential feature for PURE3D and are therefore highlighted in bold. In total, there are 32 essential questions and 11 non-essential questions.

Note that for the questionnaire, content management systems (CMSs) are regarded as synonymous to repository systems. Furthermore, it should be recognised that while those 32 features are considered "essential", it may not be practical to implement them all in the duration of the PURE3D project.

7.1.1 3D Modelling

Since PURE3D is designed for 3D scholarship, it should allow users to interact with 3D models (including both 3D objects and virtual worlds). This interaction can include creating, uploading, viewing, editing and downloading 3D models. Thus relevant questions for assessing repository systems include:

1.1. What 3D formats are supported? I consider a file format to be supported if the CMS can, e.g., store and process the format without the need to first transform it into another format.

0 (No support)	1	2	3	4 (Full support)

3D models are not supported.	The CMS supports a single 3D format. (Minimum)	Only some common 3D formats are supported. (Required)		All 3D formats are supported. (Desirable)

1.2 In what ways can the user interact with the 3D models in situ, i.e., without having to download and access them outside of PURE3D?

0 (No support)	1	2	3	4 (Full support)
The user cannot interact with 3D models in situ.	The user can navigate around 3D objects and within 3D environments. (Minimum)	The user can navigate models and adjust what is displayed via a control panel, which can include, e.g., buttons to change the time period, display annotations, etc. (Required)	The user can navigate models, adjust what is displayed and simulate the effects of performing different actions.	The user can interact with 3D models in all the aforementioned methods within a virtual world.

1.3. What facilities are provided for creating/editing 3D models in situ?

0 (No support)	1	2	3	4 (Full support)
No editing facilities are provided.		The user can assemble new 3D environments using existing 3D objects.		Functionality comparable to Blender and similar state-of-the-art software is supported (Desirable)

7.1.2 Multimedia Apparatus

This category concerns the data items that may be associated with the stored 3D models to assist users in understanding and interpreting them. These data items can include audiovisual media, text documents as well as other 3D models.

2.1. What (multimedia) file formats are supported by the CMS?

0 (No support)	1	2	3	4 (Full support)
No multimedia files are supported.		Some common file formats are supported. (Minimum / Required)		All file formats are supported. (Desirable)

2.2. In what ways can 3D models be annotated in situ?

0 (No support)	1	2	3	4 (Full support)
3D models cannot be annotated in situ.	The CMS supports the addition of pop-up boxes with texts (and hyperlinks) to 3D models.	The CMS supports the addition of pop-up boxes with embedded multimedia players.	The CMS supports pop-up boxes and allows some multimedia (e.g., maps) to be embedded into / overlayed on top of 3D models.	
	(Minimum)		(Required)	

7.1.3 Metadata

In general, metadata is data about other data; for PURE3D, I interpret "other data" as being the 3D models and their apparatus. Since rich and accurate metadata is crucial for ensuring the FAIRness of the data it describes, it is also an important consideration for PURE3D. Some related questions are:

3.1. How does the CMS generate an ID for each resource?

0 (No support)	1	2	3	4 (Full support)
No ID is assigned to each resource.	The user provides an ID for each resource manually.	The CMS generates a locally unique ID for each resource.		The CMS uses services such as DOI to assign a persistent and globally unique ID to each resource.
		(Minimum)		(Required)

3.2. What metadata descriptors can be associated with each resource?

0 (No support)	1	2	3	4 (Full support)
Resources cannot be populated with any metadata.	The CMS provides a fixed set of (possibly standardised) metadata descriptors for each resource.			The CMS supports fully customisable sets of metadata descriptors (including standardised ones) for each resource.
	(Minimum)			(Required)

3.3. What metadata values are supported by the CMS?

0 (No support)	1	2	3	4 (Full support)
Resources cannot be populated with any metadata.	The CMS supports the use of free text in the metadata entries. (Minimum)	The CMS supports the use of free text and some standardised vocabularies in the metadata. (Required)		

7.1.4 Findability / Searchability

The 'F' in FAIR refers to the findability of the data (Jacobsen et al., 2020), which implies a search engine and browser in PURE3D to enable its data to be found. This leads to questions such as:

4.1. What targets can be searched using the CMS?

0 (No support)	1	2	3	4 (Full support)
Nothing can be searched using the CMS.		The CMS can perform searches on the metadata of each resource. (Minimum / Required)		The CMS can perform searches on both the metadata and contents of each resource. (Desirable)

4.2. What type of searches can the CMS perform? I currently distinguish between two types of searches: syntactic and semantic. For example, suppose we wish to search for events that happened in year 2021 using the search term "2021". A syntactic search would return results that contain the term "2021" while a semantic search would also return results that contain the terms "twenty twenty-one" or "two thousand and twenty-one".

0 (No support)	1	2	3	4 (Full support)
Nothing can be searched using the CMS.		The CMS can perform syntactic searches. (Minimum / Required)		The CMS can perform both semantic and syntactic searches. (Desirable)

4.3. What search queries can be formulated in the CMS?

0 (No support)	1	2	3	4 (Full support)

Nothing can be searched using the CMS.	Search queries comprise a key word to be searched, e.g., "2021". (Minimum)	Search queries comprise a combination of key words. (Required)		Search queries can be expressed as a predicate in first-order logic. (Desirable)

4.4. How are search results displayed?

0 (No support)	1	2	3	4 (Full support)
Search results are not displayed.	Search results are listed in an arbitrary order. (Minimum)	Search results are listed according to some criteria (e.g., alphabetical order). (Required)		Search results can be visualised in forms other than sorted lists (e.g., world maps and timelines). (Desirable)

7.1.5 Accessibility

The second foundational principle of FAIR data is accessibility, which for the data itself refers to well-defined protocols for retrieving the data (Jacobsen et al., 2020). This leads to questions such as:

5.1. What protocols does the CMS adopt for accessing its data?

0 (No support)	1	2	3	4 (Full support)
The CMS uses closed protocols for accessing its data. (Minimum)	The CMS uses a custom API for accessing its data.	The CMS uses open and standard APIs (e.g., REST/SOAP) for accessing its data. (Required)		

5.2. What mechanisms does the CMS provide for authenticating users?

0 (No support)	1	2	3	4 (Full support)
No authentication mechanism is provided.	Users are authenticated by a typical username and password. (Minimum / Required)	Users can be authenticated also by a sign-in partner (e.g., Google) as well as a username and password. (Desirable)		The CMS supports two-factor authentication.

5.3. To what extent does the CMS adapt to different types of devices?

0 (No support)	1	2	3	4 (Full support)
The user interface is fixed.	The user interface adapts to the screen resolution.	The user interface adapts to the screen resolution and processing power.		The user interface adapts to the screen resolution, processing power, input/output modalities, etc. for all devices.
		(Desirable)		

5.4. Does the CMS support multiple languages?

0 (No support)	1	2	3	4 (Full support)
Different languages are not distinguished by the CMS.	Different languages such that the user can, e.g., choose to search/browse resources in specific languages. (Desirable)			The CMS can automatically translate between different languages.

5.5. To what extent can content creators control the access of their resources?

0 (No support)	1	2	3	4 (Full support)
No control is allowed (e.g., all data is open access).	Content creators can only set simple access rights (e.g., public or private).	Content creators can restrict and permit access to particular users and user groups.	Content creators can add other constraints on top of the access rights (e.g., to respect embargo periods).	
	(Minimum)	(Required)	(Desirable)	

5.6. What support does the CMS provide to ensure that content creators follow the best practices for web accessibility?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS provides guidelines for content	The CMS informs content creators of potential		The CMS automates the process of making its

	creators to follow.	accessibility issues. (Desirable)		content accessible.

7.1.6 Interoperability

The 'I' in FAIR represents interoperability, which means that different computer systems should be able to exchange and make use of data from each other (Jacobsen et al., 2020). Some related questions are:

6.1. What support does the CMS provide for populating the metadata of a resource?

0 (No support)	1	2	3	4 (Full support)
No support is provided for completing a metadata entry.	The CMS provides a form with textboxes for users to fill in.	The CMS provides a form with the option to search for terms in standardised vocabularies.		Rich metadata is automatically created by the CMS.
	(Minimum)	(Required)		

6.2. What metadata formats/schemas are supported by the CMS?

0 (No support)	1	2	3	4 (Full support)
Resources cannot be associated with any metadata.	The CMS adopts a single, fixed (possibly standardised) metadata schema for each resource.	The CMS allows limited flexibility in the choosing the metadata schema for each resource.		The CMS supports all possible standardised and user-specified metadata descriptors.
	(Minimum)	(Required)		(Desirable)

6.3. To what extent can the CMS be linked with other similar repositories?

0 (No support)	1	2	3	4 (Full support)
The CMS exists as a silo.	The CMS can be registered in popular registries for similar repositories.	The CMS is registered and related research portals and repositories can harvest data from the CMS.	The CMS is registered, can be harvested and can harvest data from other repositories.	
(Minimum)	(Required)		(Desirable)	

7.1.7 Reusability / Quality Management

The fourth and last principle of FAIR data is reusability (Jacobsen et al., 2020), which I believe is dependent on sound quality management. In other words, to maximise reuse of its 3D models, I believe the infrastructure should help users to: (1) maximise the quality (historical rigour, authenticity, etc.) of their models, and (2) assess whether pre-existing models are of sufficient quality for their purposes.

7.1. What measures does the CMS adopt to assure the quality of its (meta)data?

0 (No support)	1	2	3	4 (Full support)
No quality control measures are adopted.	The CMS provides guidelines that content creators can follow.	The CMS provides guidelines and/or performs checks automatically on the data. (Desirable)	The CMS requires all data to be peer-reviewed before it can be made accessible.	

7.2. What support does the CMS provide for content creators to document uncertainty, alternative hypotheses, changes over time, etc. on their 3D models?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS provides guidelines that content creators can follow.	The CMS provides guidelines and example 3D models that content creators can reuse. (Minimum)	The CMS provides guidelines, examples and a toolkit for adding such information onto 3D models. (Required)	

7.1.8 Standards & Legislation

The PURE3D infrastructure should comply with the relevant standards and legislation. For example, users should be provided with clear terms and conditions of use as well as privacy policies. This leads to questions such as:

8.1. Is the CMS compliant to the relevant standards/legislation?

0 (No support)	1	2	3	4 (Full support)
No				Yes (Minimum / Required)

8.2. What support does the CMS provide for archiving resources in standard formats?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS warns users of resources not in standard data formats. (Desirable)			The CMS automatically saves a copy of all resources in standard data formats.

8.3. In what ways can users report inappropriate content in the CMS (other than by e-mailing the team)?

0 (No support)	1	2	3	4 (Full support)
Users cannot report inappropriate content.	The CMS provides a generic form for reporting inappropriate content.	The CMS supports fine-grained reporting on its contents. (Desirable)		

8.4. What support does the CMS provide to help content creators determine the appropriate level of access (and copyright) for their resources?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS provides guidelines to content creators.	The CMS provides a questionnaire to determine the appropriate level of access. (Desirable)		

7.1.9 Maintainability

The PURE3D infrastructure must be easy to maintain to help ensure that it remains operational in the long term. This raises questions such as:

9.1. Is the CMS open source?

0 (No support)	1	2	3	4 (Full support)
No				Yes (Minimum / Required)

9.2. What support does the CMS provide for handling system updates?

0 (No support)	1	2	3	4 (Full support)
No support is provided.		The CMS detects when updates are		The CMS automatically applies any

		available and notifies the system maintainers.		available updates (after manual confirmation). (Desirable)

9.3. What support does the CMS provide for maintaining its contents, such as to migrate to a different data format?

0 (No support)	1	2	3	4 (Full support)
No support is provided.		The CMS alerts content creators that their resources need to be updated.		The CMS automatically updates its resources (after manual confirmation). (Desirable)

7.1.10 Safety & Security

The users of the system should be protected from any system errors and malicious actors, which raises questions such as the following:

10.1. In what ways does the CMS protect its resources from corruption due to hardware or software failures?

0 (No support)	1	2	3	4 (Full support)
No protection is provided.	The CMS can detect and alert content creators when their resources are corrupted. (Desirable)			The CMS can automatically recover corrupted resources.

10.2. In what ways does the CMS protect its users from malware?

0 (No support)	1	2	3	4 (Full support)
No protection is provided.	The CMS provides a sandbox for users to view/interact with is resources. (Minimum / Required)			The CMS provides a sandbox and scans all its resources for malware. (Desirable)

10.3. Can the CMS handle unexpected system failures, user inputs, user traffic, etc.?

0 (No support)	1	2	3	4 (Full support)
No				Yes

				(Minimum / Required)

10.4. Can the CMS keep an audit trail of all user and system activity?

0 (No support)	1	2	3	4 (Full support)
No				Yes (Minimum / Required)

7.1.11 Community Engagement

To help prevent the system from becoming obsolete, it may be useful for the system to promote community engagement, such as by providing user tutorials and manuals as well as by pushing updates to subscribers. Questions under this category include:

11.1. What level of community participation does the CMS allow?

0 (No support)	1	2	3	4 (Full support)
No participation is allowed.	Any user can browse and view the resources anonymously (if permitted by the content creator). (Minimum / Required)	Any user can provide private feedback on the CMS and its resources.	Any user can provide feedback and view feedback from other users.	

11.2. What support does the CMS provide to help users use the system?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS provides detailed documentation of its user interface. (Minimum / Required)	The CMS provides tutorials for its users. (Desirable)		

11.3. In what ways does the CMS make use of usage statistics?

0 (No support)	1	2	3	4 (Full support)
The CMS does not collect or use usage statistics.	The CMS collects usage statistics and provides reports to the	The CMS provides usage statistics and uses them to generate		

	appropriate users. (Minimum / Required)	user-specific recommendations.		

11.4. What support does the CMS provide for users to share its contents?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS creates shareable links (e.g., DOIs) to its resources (and user collections) (Minimum / Required)	The CMS provides links as well as embeddable viewers for its resources. (Desirable)		

11.5. In what ways does the CMS make use of social media?

0 (No support)	1	2	3	4 (Full support)
The CMS doesn't make use of social media.	The CMS allows users to subscribe to updates. (Minimum / Required)	The CMS publishes updates to its subscribers and also broadcasts them using social media (e.g., Twitter). (Desirable)		

7.1.12 Research Support

To help prevent the system from becoming obsolete, it may be useful for the system to promote community engagement, such as by providing user tutorials and manuals as well as by pushing updates to subscribers. Questions under this category include:

12.1. What support does the CMS provide to users for performing research on its 3D models?

0 (No support)	1	2	3	4 (Full support)
No support is provided.		The CMS allows users to create private workspace with some tools for conducting research (e.g., for adding		The CMS provides a complete suite of analytical tools for users to study its resources.

		private annotations). (Minimum / Required)		(Desirable)

12.2. What support does the CMS provide to facilitate collaborations?

0 (No support)	1	2	3	4 (Full support)
No support is provided.		The CMS allows users to share a workspace / specific resources with each other.		The CMS allows users to share resources and to network with each other.
(Minimum)		(Required)		(Desirable)

12.3. What support does the CMS provide for publishing the stored 3D models?

0 (No support)	1	2	3	4 (Full support)
No support is provided.	The CMS can automatically generate citations for its resources.	The CMS generates citations and provides facilities for conducting peer reviews.		
	(Minimum / Required)	(Desirable)		

12.4. What version control system does the CMS provide?

0 (No support)	1	2	3	4 (Full support)
No version control is supported.	The CMS allows users to replace old resources with updated versions.			The CMS can keep track of all the changes between the old and updated versions.
	(Minimum / Required)			(Desirable)

7.2 Comparison Results

The table on the following pages contains the results of scoring each of the 21 repository systems according to the rubric presented in the previous section. For convenience, an asterisk next to each question is used to denote that the corresponding system feature is deemed to be "essential" for PURE3D. The repository systems were scored based solely on the information readily available online, thus it may contain inaccuracies and may be incomplete. Indeed, functionality provided by extensions to the systems are ignored. Furthermore, for features with no information available, the corresponding cell is left blank.

			System										
			Institutional Data Repositories							**Digital Asset Management System**			
Category	**Feature**		DSpace	EPrints	Fedora	OJS	Invenio	Dataverse	CKAN	Phraseanet	Pimcore	ResourceSpace	EnterMedia
3D Modelling	*	1.1. What 3D formats are supported?											
	*	1.2. In what ways can the user interact with the 3D models in situ?											
		1.3. What facilities are provided for creating/editing 3D models in situ?											
Multimedia Apparatus	*	2.1. What (multimedia) file formats are supported by the CMS?	3		3		3		2	3	3	3	
	*	2.2. In what ways can 3D models be annotated in situ?											
Metadata	*	3.1. How does the CMS generate an ID for each resource?											
	*	3.2. What metadata descriptors can be associated with each resource?	4		2		2	2	2	2	3	3	
	*	3.3. What metadata values are supported by the CMS?											
Findability / Searchability	*	4.1. What targets can be searched using the CMS?	3		1		3	3	3	2		2	
	*	4.2. What type of searches can the CMS perform?											
	*	4.3. What search queries can be formulated in the CMS?					3		3			3	
	*	4.4. How are search results displayed?	2									2	
Accessibility	*	5.1. What protocols does the CMS adopt for accessing its data?	2		2		2	2	1	2	1		
	*	5.2. What mechanisms does the CMS provide for authenticating users?	2		2		3	2		2		2	
		5.3. To what extent does the CMS adapt to different types of devices?									1		
		5.4. Does the CMS support multiple languages?	1							1	1	1	
	*	5.5. To what extent can content creators control the access of their resources?			2		2	2		2			
		5.6. What support does the CMS provide to ensure that content creators follow the best practices for web accessibility?											
Interoperability	*	6.1. What support does the CMS provide for populating the metadata of a resource?								2		2	
	*	6.2. What metadata formats/schemas are supported by the CMS?	3				2	2	2				
	*	6.3. To what extent can the CMS be linked with other similar repositories?						2	2				
Reusability / Quality Management		7.1. What measures does the CMS adopt to assure the quality of its (meta)data?											
	*	7.2. What support does the CMS provide for content creators to document uncertainty, alternative hypotheses, changes over time, etc. on their 3D models?											

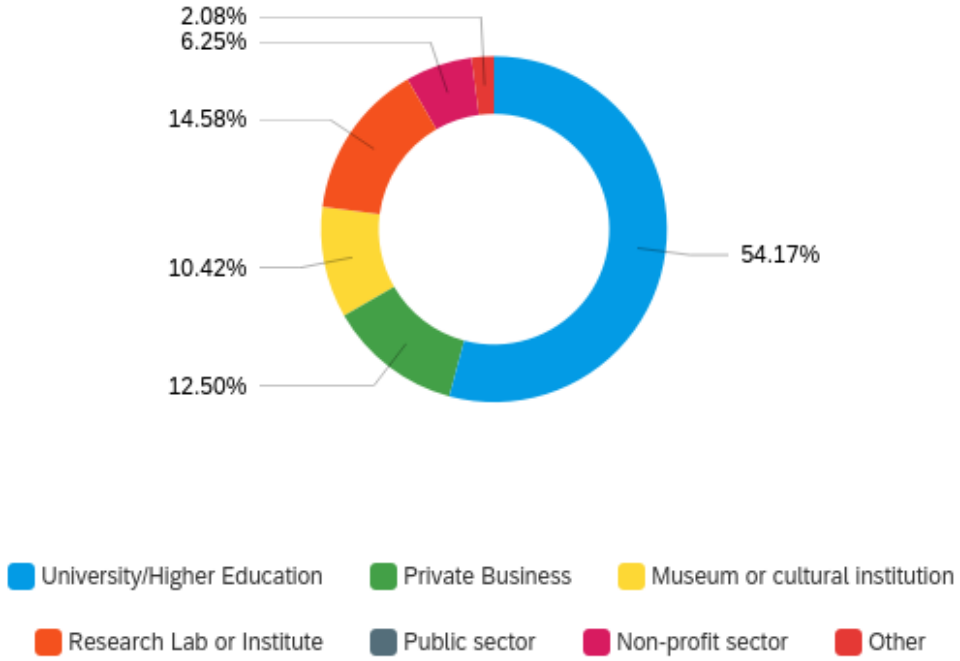
					Content Management System				Digital Cultural Heritage Repository			
Category		**Feature**	Razuna	Nuxeo DAM	Drupal	Joomla	SilverStripe	WordPress	Arches	Mukurtu	Omeka	Scalar
3D Modelling	*	1.1. What 3D formats are supported?										
	*	1.2. In what ways can the user interact with the 3D models in situ?							1			
		1.3. What facilities are provided for creating/editing 3D models in situ?										
Multimedia Apparatus	*	2.1. What (multimedia) file formats are supported by the CMS?	3	3	3		2	3		2		3
	*	2.2. In what ways can 3D models be annotated in situ?										
Metadata	*	3.1. How does the CMS generate an ID for each resource?										
	*	3.2. What metadata descriptors can be associated with each resource?						4		2	1	2
	*	3.3. What metadata values are supported by the CMS?							2		3	2
Findability / Searchability	*	4.1. What targets can be searched using the CMS?	3	1					3		3	
	*	4.2. What type of searches can the CMS perform?							3			
	*	4.3. What search queries can be formulated in the CMS?										
	*	4.4. How are search results displayed?							4			
Accessibility	*	5.1. What protocols does the CMS adopt for accessing its data?	1									2
	*	5.2. What mechanisms does the CMS provide for authenticating users?				4						
		5.3. To what extent does the CMS adapt to different types of devices?										
		5.4. Does the CMS support multiple languages?			2	1	1	1				
	*	5.5. To what extent can content creators control the access of their resources?	2			2		2	2	2		
		5.6. What support does the CMS provide to ensure that content creators follow the best practices for web accessibility?			2							
Interoperability	*	6.1. What support does the CMS provide for populating the metadata of a resource?							2		2	
	*	6.2. What metadata formats/schemas are supported by the CMS?	1						2			
	*	6.3. To what extent can the CMS be linked with other similar repositories?										
Reusability / Quality Management		7.1. What measures does the CMS adopt to assure the quality of its (meta)data?										
	*	7.2. What support does the CMS provide for content creators to document uncertainty, alternative hypotheses, changes over time, etc. on their 3D models?										

			System										
			Institutional Data Repositories							Digital Asset Management System			
Category		**Feature**	DSpace	EPrints	Fedora	OJS	Invenio	Dataverse	CKAN	Phraseanet	Pimcore	ResourceSpace	EnterMedia
Standards & Legislation	*	8.1. Is the CMS compliant to the relevant standards/legislation?											
		8.2. What support does the CMS provide for archiving resources in standard formats?											
		8.3. In what ways can users report inappropriate content in the CMS (other than by e-mailing the team)?											
		8.4. What support does the CMS provide to help content creators determine the appropriate level of access (and copyright) for their resources?											
Maintainability	*	9.1. Is the CMS open source?	4		4	4	4	4	4	4	4	4	
		9.2. What support does the CMS provide for handling system updates?											
		9.3. What support does the CMS provide for maintaining its contents, such as to migrate to a different data format?											
Safety & Security		10.1. In what ways does the CMS protect its resources from corruption due to hardware or software failures?											
	*	10.2. In what ways does the CMS protect its users from malware?											
	*	10.3. Can the CMS handle unexpected system failures, user inputs, user traffic, etc.?											
	*	10.4. Can the CMS keep an audit trail of all user and system activity?			4		4			4	4	4	
Community Engagement	*	11.1. What level of community participation does the CMS allow?									1	1	
	*	11.2. What support does the CMS provide to help users use the system?											
	*	11.3. In what ways does the CMS make use of usage statistics?						1		1	2	1	
	*	11.4. What support does the CMS provide for users to share its contents?						1		1		2	
	*	11.5. In what ways does the CMS make use of social media?								2	2	2	
Research Support	*	12.1. What support does the CMS provide to users for performing research on its 3D models?											
	*	12.2. What support does the CMS provide to facilitate collaborations?										2	
	*	12.3. What support does the CMS provide for publishing the stored 3D models?				2		2	2	2		2	
	*	12.4. What version control system does the CMS provide?			2		2	2		2	2	2	

					Content Management System				Digital Cultural Heritage Repository			
Category		**Feature**	Razuna	Nuxeo DAM	Drupal	Joomla	SilverStripe	WordPress	Arches	Mukurtu	Omeka	Scalar
Standards & Legislation	*	8.1. Is the CMS compliant to the relevant standards/legislation?										
		8.2. What support does the CMS provide for archiving resources in standard formats?										
		8.3. In what ways can users report inappropriate content in the CMS (other than by e-mailing the team)?	2									
		8.4. What support does the CMS provide to help content creators determine the appropriate level of access (and copyright) for their resources?										
Maintainability	*	9.1. Is the CMS open source?	4	4	4	4	4	4	4	4	4	4
		9.2. What support does the CMS provide for handling system updates?										
		9.3. What support does the CMS provide for maintaining its contents, such as to migrate to a different data format?										
Safety & Security		10.1. In what ways does the CMS protect its resources from corruption due to hardware or software failures?										
	*	10.2. In what ways does the CMS protect its users from malware?										
	*	10.3. Can the CMS handle unexpected system failures, user inputs, user traffic, etc.?										
	*	10.4. Can the CMS keep an audit trail of all user and system activity?		4					4			4
Community Engagement	*	11.1. What level of community participation does the CMS allow?	2	1				3		3	3	3
	*	11.2. What support does the CMS provide to help users use the system?										
	*	11.3. In what ways does the CMS make use of usage statistics?										
	*	11.4. What support does the CMS provide for users to share its contents?	2	2			2					
	*	11.5. In what ways does the CMS make use of social media?		2				2				
Research Support	*	12.1. What support does the CMS provide to users for performing research on its 3D models?								2		
	*	12.2. What support does the CMS provide to facilitate collaborations?	2	2						2		
	*	12.3. What support does the CMS provide for publishing the stored 3D models?		2			2					
	*	12.4. What version control system does the CMS provide?	1			1	1	4	1			2

8 Appendix C - Survey Results

Q2 - In which sector do you work?

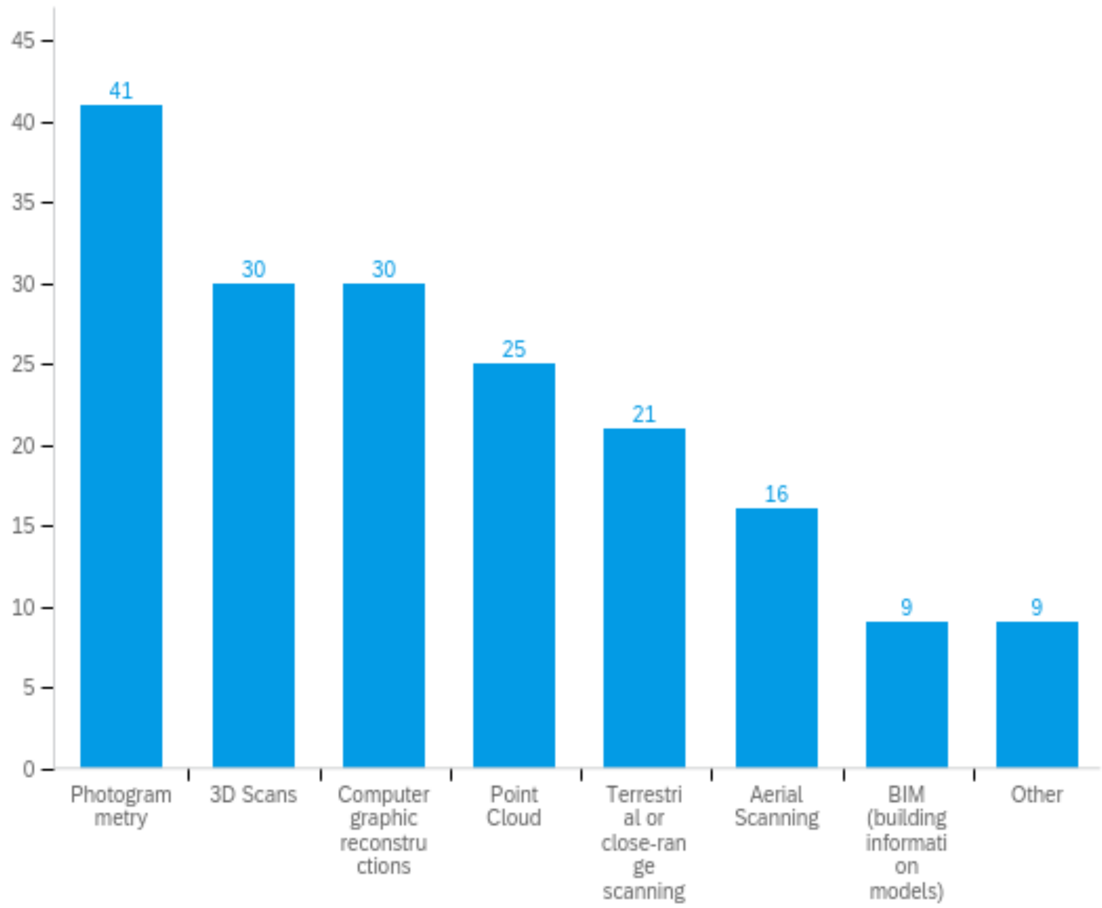


#	Answer	%	Count
1	University/Higher Education	54.17%	26
2	Private Business	12.50%	6
3	Museum or cultural institution	10.42%	5
4	Research Lab or Institute	14.58%	7
5	Public sector	0.00%	0
7	Non-profit sector	6.25%	3
8	Other	2.08%	1
	Total	100%	48

Other - Text

1. Academic museum (so both higher ed & museum)

Q3 - What kinds of 3D models do you create and/or work with?

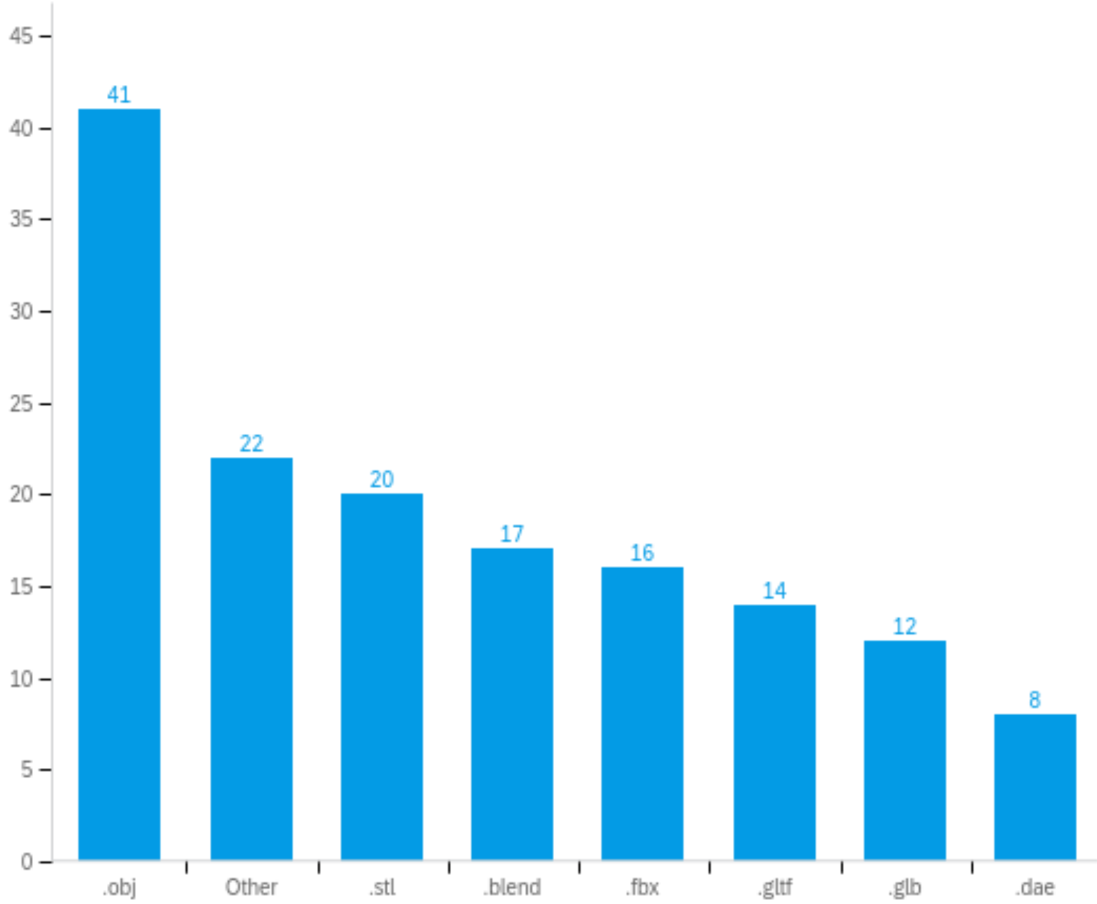


#	Answer	%	Count
1	3D Scans	16.57%	30
2	Computer graphic reconstructions	16.57%	30
3	Point Cloud	13.81%	25
4	BIM (building information models)	4.97%	9
5	Aerial Scanning	8.84%	16
6	Other	4.97%	9
7	Photogrammetry	22.65%	41
8	Terrestrial or close-range scanning	11.60%	21
	Total	100%	181

Other - Text

1. Mocap and Game Assets for educational purposes
2. All of them
3. physically-based rendering
4. RTI, VFX, Animation,
5. Tomography
6. micro CT
7. Geophysical data

Q4 - Which 3D file formats do you most commonly use?

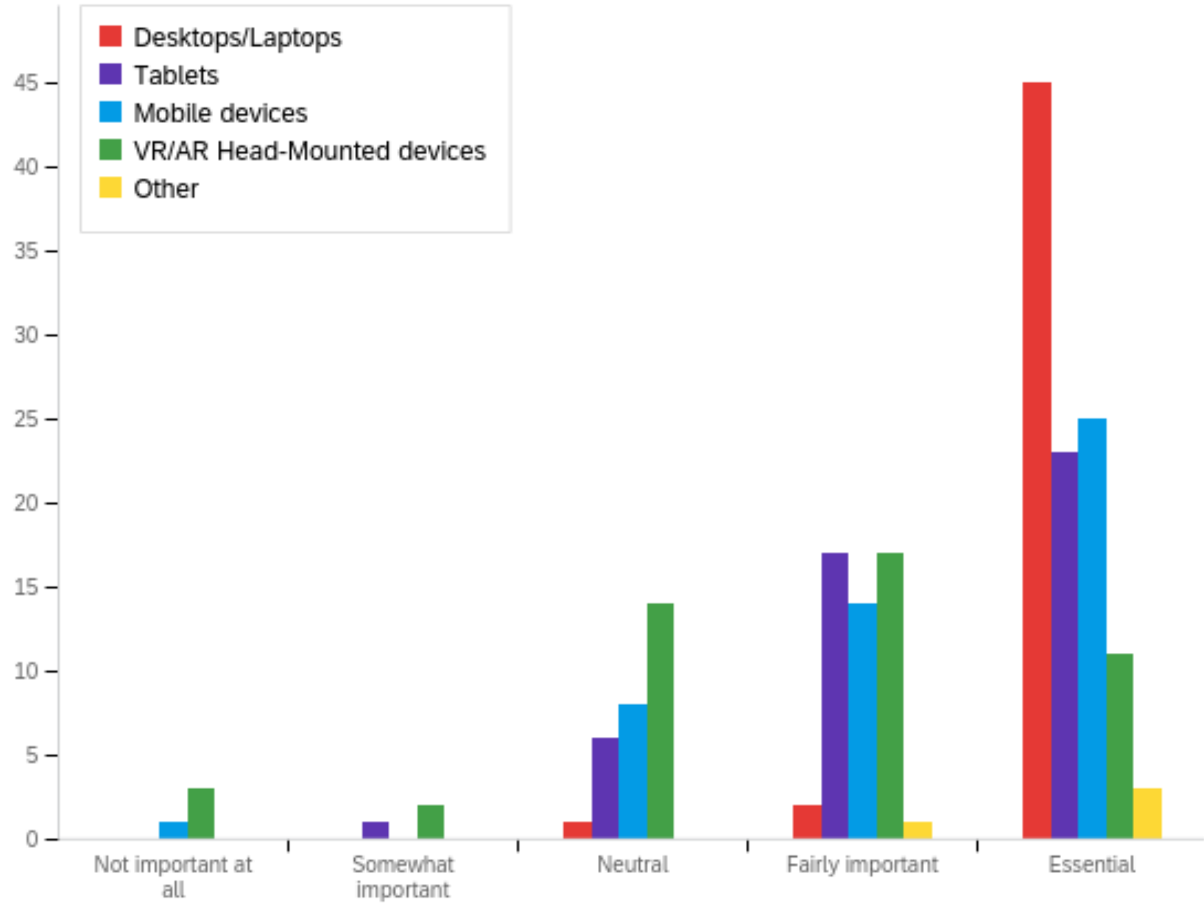


#	Answer	%	Count
1	.obj	27.33%	41
2	.fbx	10.67%	16
3	.blend	11.33%	17
4	.dae	5.33%	8
5	.gltf	9.33%	14
6	.glb	8.00%	12
7	.stl	13.33%	20
8	Other	14.67%	22
	Total	100%	150

Other - Text

1. c4d
2. .las;.ply
3. ply
4. xyz, ply
5. PLY; LAZ; TIFF (DEM)
6. .abc, alembic
7. .ply
8. 3ds, ply, E57
9. .ply
10. .ply .wrl
11. stp csg
12. .ply
13. .svx
14. c4d
15. ply
16. Usd
17. x3d

Q5 - An end-user of the 3D web viewer should be able to access the 3D model and scene with...



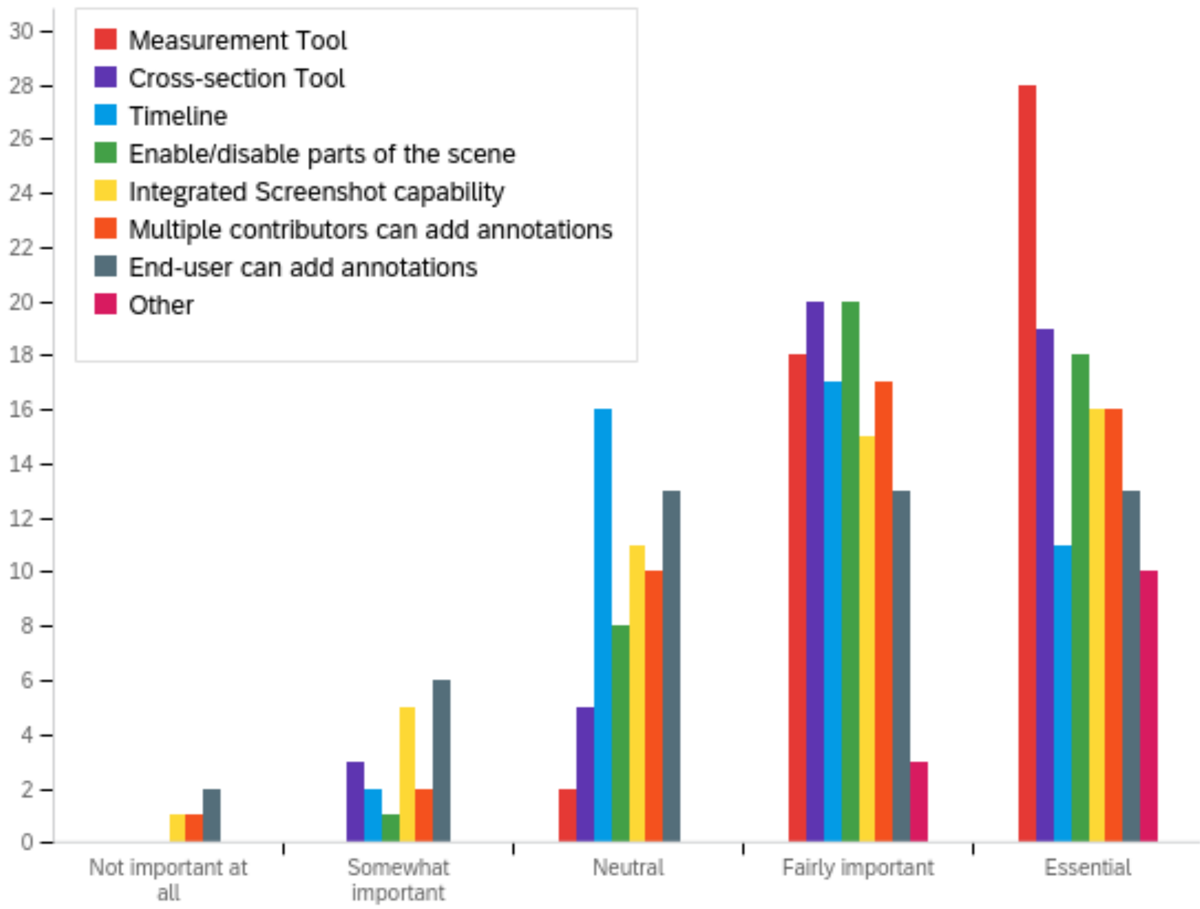
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Desktops/Laptops	3.00	5.00	4.92	0.34	0.12	48
2	Tablets	2.00	5.00	4.32	0.77	0.60	47
3	Mobile devices	1.00	5.00	4.29	0.89	0.79	48
4	VR/AR Head-Mounted devices	1.00	5.00	3.66	1.08	1.16	47
5	Other	4.00	5.00	4.75	0.43	0.19	4

#	Question	Not important at all		Somewhat important		Neutral		Fairly important		Essential		Total
1	Desktops/Laptops	0.00%	0	0.00%	0	2.08%	1	4.17%	2	93.75%	45	48
2	Tablets	0.00%	0	2.13%	1	12.77%	6	36.17%	17	48.94%	23	47
3	Mobile devices	2.08%	1	0.00%	0	16.67%	8	29.17%	14	52.08%	25	48
4	VR/AR Head-Mounted devices	6.38%	3	4.26%	2	29.79%	14	36.17%	17	23.40%	11	47
5	Other	0.00%	0	0.00%	0	0.00%	0	25.00%	1	75.00%	3	4

Other - Text

1. Low end devices

Q6 - The 3D web viewer should support the following features...



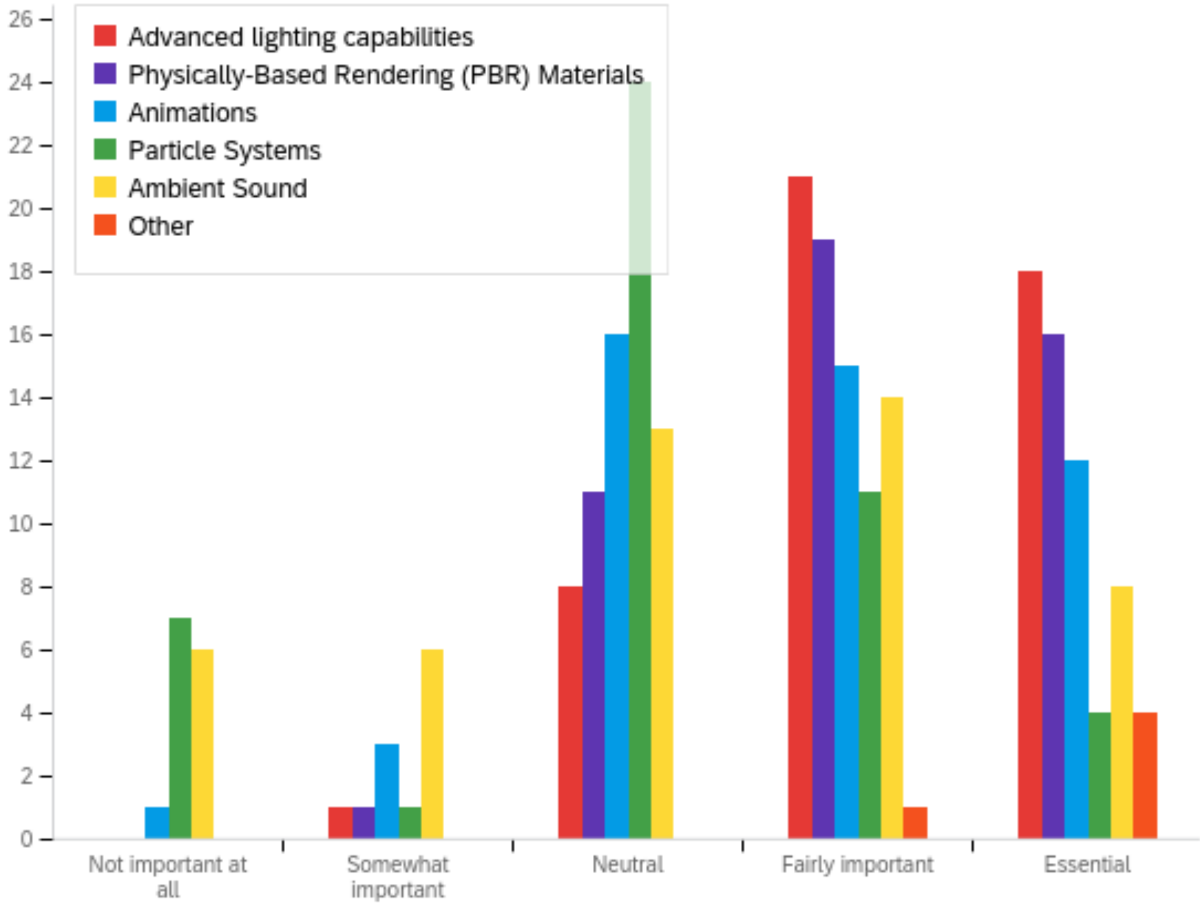
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Measurement Tool	3.00	9.00	8.38	1.22	1.48	48
2	Cross-section Tool	2.00	9.00	7.49	2.26	5.10	47
3	Timeline	2.00	9.00	6.24	2.72	7.40	46
4	Enable/disable parts of the scene	2.00	9.00	7.40	2.25	5.05	47
5	Integrated Screenshot capability	1.00	9.00	6.42	2.89	8.33	48
6	Multiple contributors can add annotations	1.00	9.00	6.85	2.66	7.09	46
7	End-user can add annotations	1.00	9.00	5.83	3.03	9.16	47
8	Other	8.00	9.00	8.77	0.42	0.18	13

#	Question	Not important at all		Somewhat important		Neutral		Fairly important		Essential		Total
1	Measurement Tool	0.00%	0	0.00%	0	4.17%	2	37.50%	18	58.33%	28	48
2	Cross-section Tool	0.00%	0	6.38%	3	10.64%	5	42.55%	20	40.43%	19	47
3	Timeline	0.00%	0	4.35%	2	34.78%	16	36.96%	17	23.91%	11	46
4	Enable/disable parts of the scene	0.00%	0	2.13%	1	17.02%	8	42.55%	20	38.30%	18	47
5	Integrated Screenshot capability	2.08%	1	10.42%	5	22.92%	11	31.25%	15	33.33%	16	48
6	Multiple contributors can add annotations	2.17%	1	4.35%	2	21.74%	10	36.96%	17	34.78%	16	46
7	End-user can add annotations	4.26%	2	12.77%	6	27.66%	13	27.66%	13	27.66%	13	47
8	Other	0.00%	0	0.00%	0	0.00%	0	23.08%	3	76.92%	10	13

Other - Text

1. matterport like tours for low end devices for 100% CGI models
2. Support UTM coordinates
3. complex annotations (i.e., urls for possibly linking entire reports/tables/webpages)
4. way to cite/show underlying source data
5. PBR shader, mumtiple lighting, references, verification tools (quality), linkable (integration)
6. Uncertainty in the reconstruction
7. choice of shaders
8. Permissions
9. view mesh without texture
10. Model comparison with accurate scale
11. Integrated Evidence/Hypothesis Scale
12. Download of data
13. multiple texture/data channels

Q7 - The 3D web viewer should be able to handle...



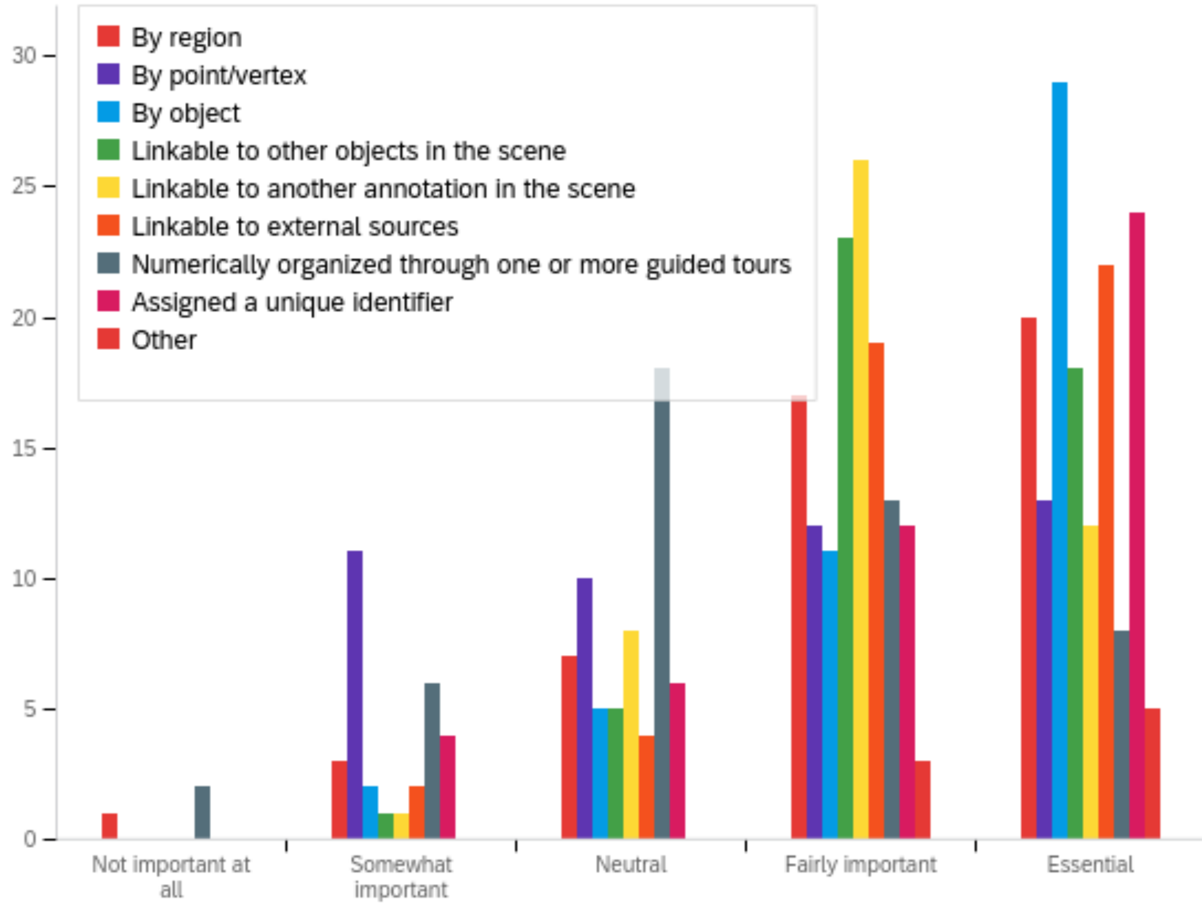
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Advanced lighting capabilities	2.00	7.00	5.79	1.47	2.16	48
2	Physically-Based Rendering (PBR) Materials	2.00	7.00	5.55	1.61	2.59	47
3	Animations	1.00	7.00	4.87	1.90	3.60	47
4	Particle Systems	1.00	7.00	3.72	1.89	3.56	47
5	Ambient Sound	1.00	7.00	4.19	2.15	4.62	47
6	Other	6.00	7.00	6.80	0.40	0.16	5

#	Question	Not important at all		Somewhat important		Neutral		Fairly important		Essential		Total
1	Advanced lighting capabilities	0.00%	0	2.08%	1	16.67%	8	43.75%	21	37.50%	18	48
2	Physically-Based Rendering (PBR) Materials	0.00%	0	2.13%	1	23.40%	11	40.43%	19	34.04%	16	47
3	Animations	2.13%	1	6.38%	3	34.04%	16	31.91%	15	25.53%	12	47
4	Particle Systems	14.89%	7	2.13%	1	51.06%	24	23.40%	11	8.51%	4	47
5	Ambient Sound	12.77%	6	12.77%	6	27.66%	13	29.79%	14	17.02%	8	47
6	Other	0.00%	0	0.00%	0	0.00%	0	20.00%	1	80.00%	4	5

Other - Text

1. Easy navigation and keyboard access for accessibility for non mouse users
2. verification tool (quality)
3. webGPU

Q8 - Annotations within the 3D web viewer should be....



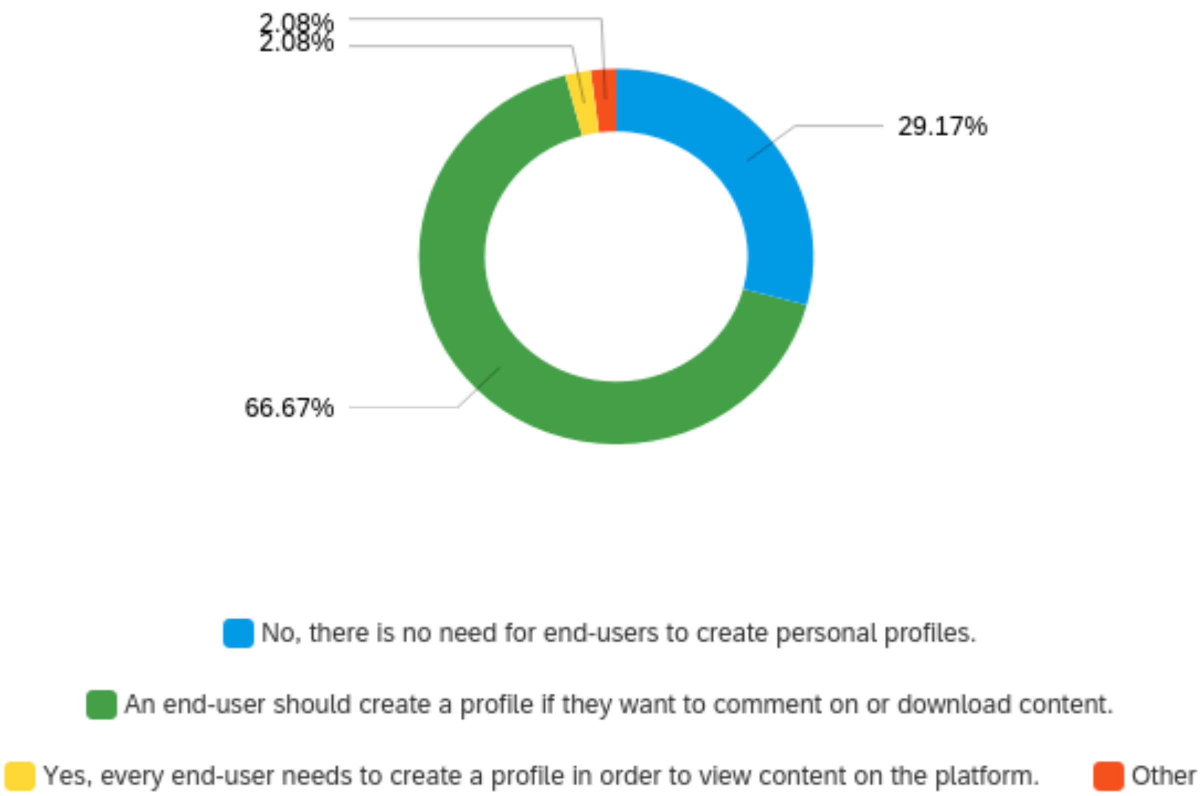
#	Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	By region	1.00	5.00	4.08	1.00	0.99	48
2	By point/vertex	2.00	5.00	3.59	1.13	1.29	46
3	By object	2.00	5.00	4.43	0.84	0.71	47
4	Linkable to other objects in the scene	2.00	5.00	4.23	0.72	0.52	47
5	Linkable to another annotation in the scene	2.00	5.00	4.04	0.71	0.51	47
6	Linkable to external sources	2.00	5.00	4.30	0.80	0.63	47
7	Numerically organized through one or more guided tours	1.00	5.00	3.40	1.04	1.09	47
8	Assigned a unique identifier	2.00	5.00	4.22	0.98	0.95	46
9	Other	4.00	5.00	4.63	0.48	0.23	8

#	Question	Not important at all		Somewhat important		Neutral		Fairly important		Essential		Total
1	By region	2.08%	1	6.25%	3	14.58%	7	35.42%	17	41.67%	20	48
2	By point/vertex	0.00%	0	23.91%	11	21.74%	10	26.09%	12	28.26%	13	46
3	By object	0.00%	0	4.26%	2	10.64%	5	23.40%	11	61.70%	29	47
4	Linkable to other objects in the scene	0.00%	0	2.13%	1	10.64%	5	48.94%	23	38.30%	18	47
5	Linkable to another annotation in the scene	0.00%	0	2.13%	1	17.02%	8	55.32%	26	25.53%	12	47
6	Linkable to external sources	0.00%	0	4.26%	2	8.51%	4	40.43%	19	46.81%	22	47
7	Numerically organized through one or more guided tours	4.26%	2	12.77%	6	38.30%	18	27.66%	13	17.02%	8	47
8	Assigned a unique identifier	0.00%	0	8.70%	4	13.04%	6	26.09%	12	52.17%	24	46
9	Other	0.00%	0	0.00%	0	0.00%	0	37.50%	3	62.50%	5	8

Other - Text

1. Multi language support
2. Linkable from external resources
3. related to a specific user
4. Exportable / Standardized
5. By faces

Q9 - Should end-users create a personal profile?

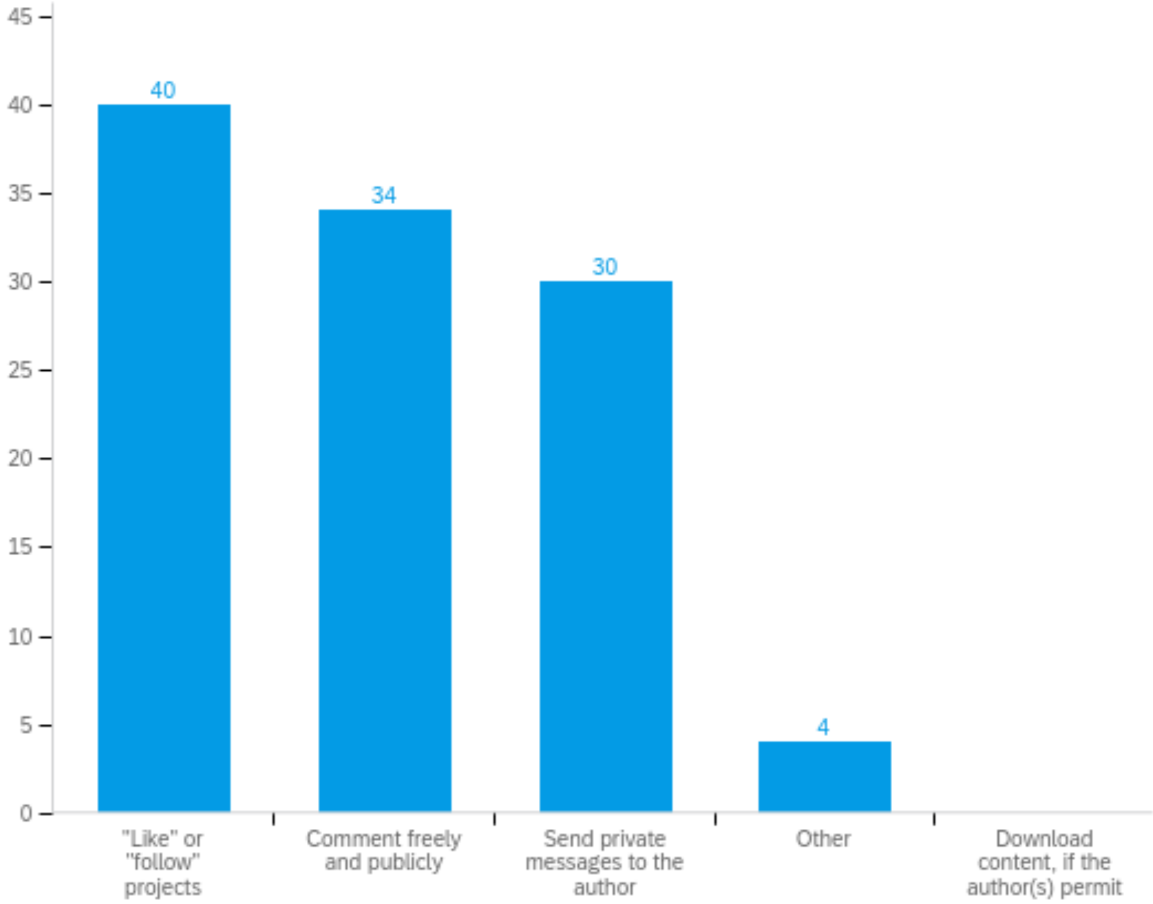


#	Answer	%	Count
1	No, there is no need for end-users to create personal profiles.	29.17%	14
2	An end-user should create a profile if they want to comment on or download content.	66.67%	32
3	Yes, every end-user needs to create a profile in order to view content on the platform.	2.08%	1
4	Other	2.08%	1
	Total	100%	48

Other - Text

1. All the above solutions. Its depends on the access restrictions chosen by the right owner of the 3D object chosen by the cr

Q10 - End-users of the 3D content may...

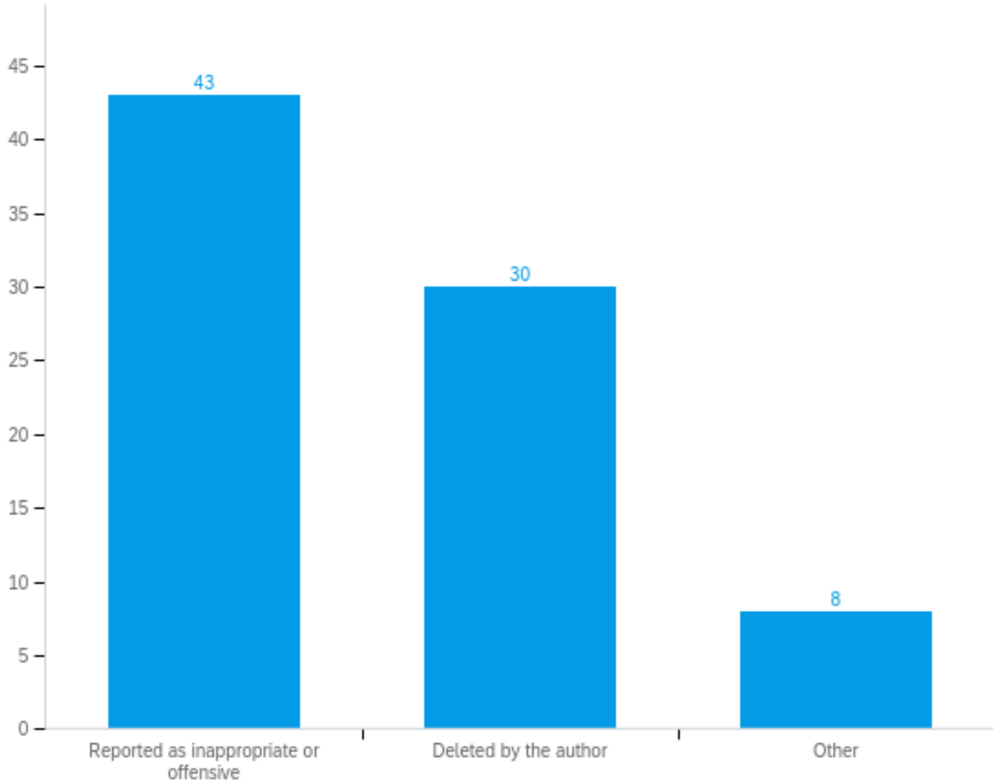


#	Answer	%	Count
1	Comment freely and publicly	31.48%	34
2	Send private messages to the author	27.78%	30
3	"Like" or "follow" projects	37.04%	40
4	Other	3.70%	4
5	Download content, if the author(s) permit	0.00%	0
	Total	100%	108

Other - Text

1. Comment privately
2. Make annotations to improve the 3D content by author
3. Download w/o permission

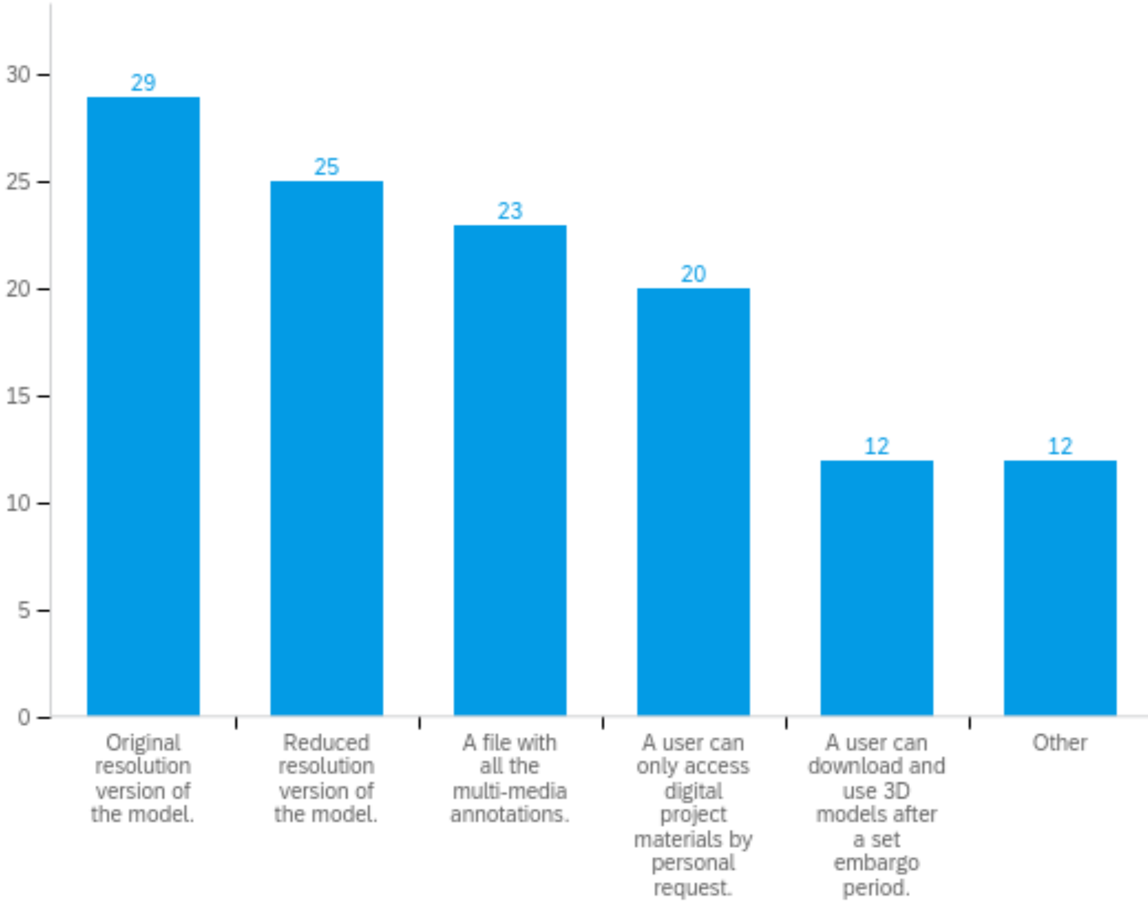
Q11 - Public comments may be...



#	Answer	%	Count
1	Reported as inappropriate or offensive	53.09%	43
2	Deleted by the author	37.04%	30
4	Other	9.88%	8
	Total	100%	81

Other - Text
1. not possible
2. disabled on a given model by the creator
3. Spam filtered
4. No public comments
5. Public comments should not be present at all
6. Answered by the author
7. Mediated by curator

Q12 - End-users should be able to download and use/reuse...

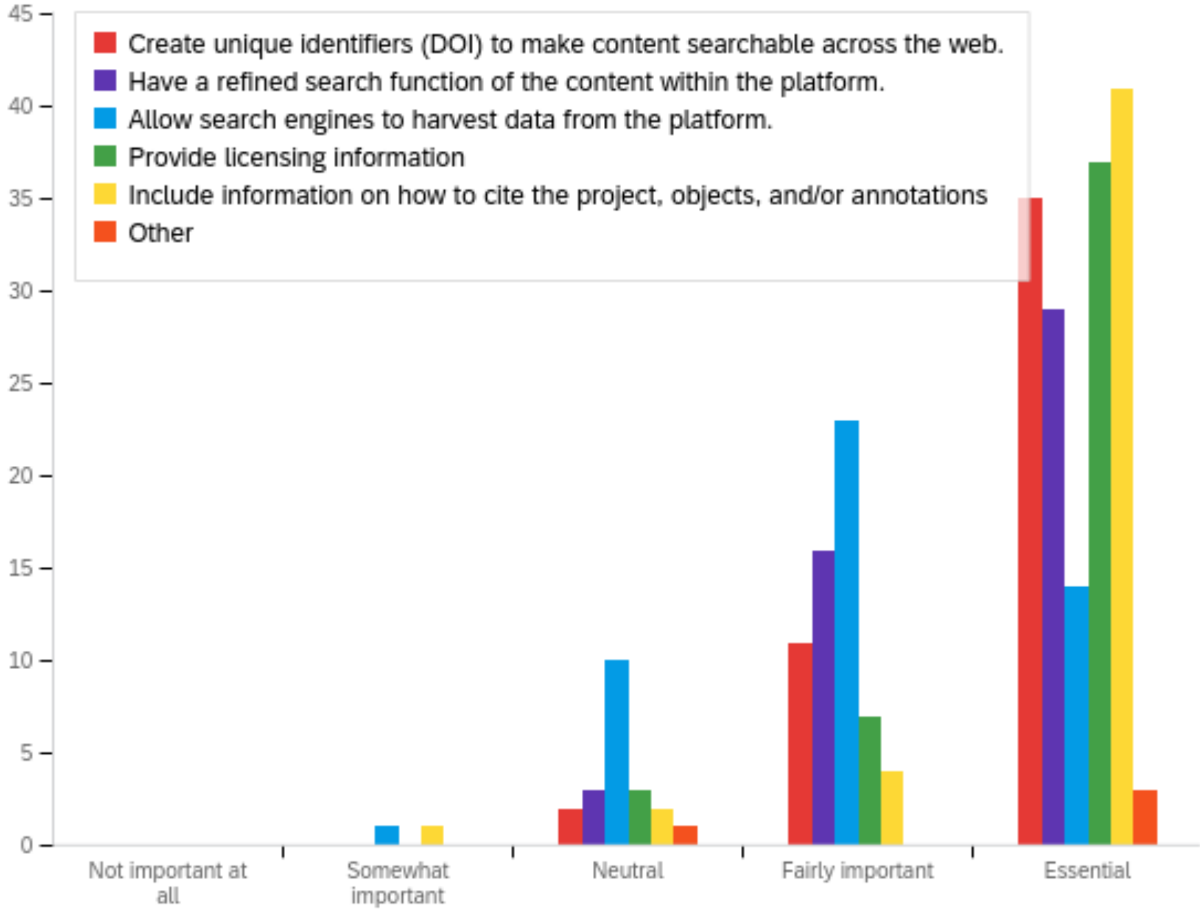


#	Answer	%	Count
1	Original resolution version of the model.	23.97%	29
2	Reduced resolution version of the model.	20.66%	25
3	A file with all the multi-media annotations.	19.01%	23
5	A user can only access digital project materials by personal request.	16.53%	20
6	A user can download and use 3D models after a set embargo period.	9.92%	12
8	Other	9.92%	12
	Total	100%	121

Other - Text

1. Has to be defined by resource
2. All of them, but it depends on the author will.
3. possible API access enabled at some point for analysis of 3d files as data
4. These settings should be determined by the model owner
5. This should be left to decide by the modeller on a case-by-case basis
6. depends on context and sensitivity issues
7. Creative Commons licensing
8. Metadata and paradata for the model and its creation process
9. Its depends on the access rights on the object.
10. All of above with author permission for derivative creations. For public collections, original full resolution scans should be made available after the initial, limited embargo period allowing for the researcher to publish.
11. Original resolution version of the model by personal request to the author
12. A robust system should be able to accommodate all of those scenarios, depending on the content and its community of origin

Q13 - In addition to web-viewing capabilities, the platform should...



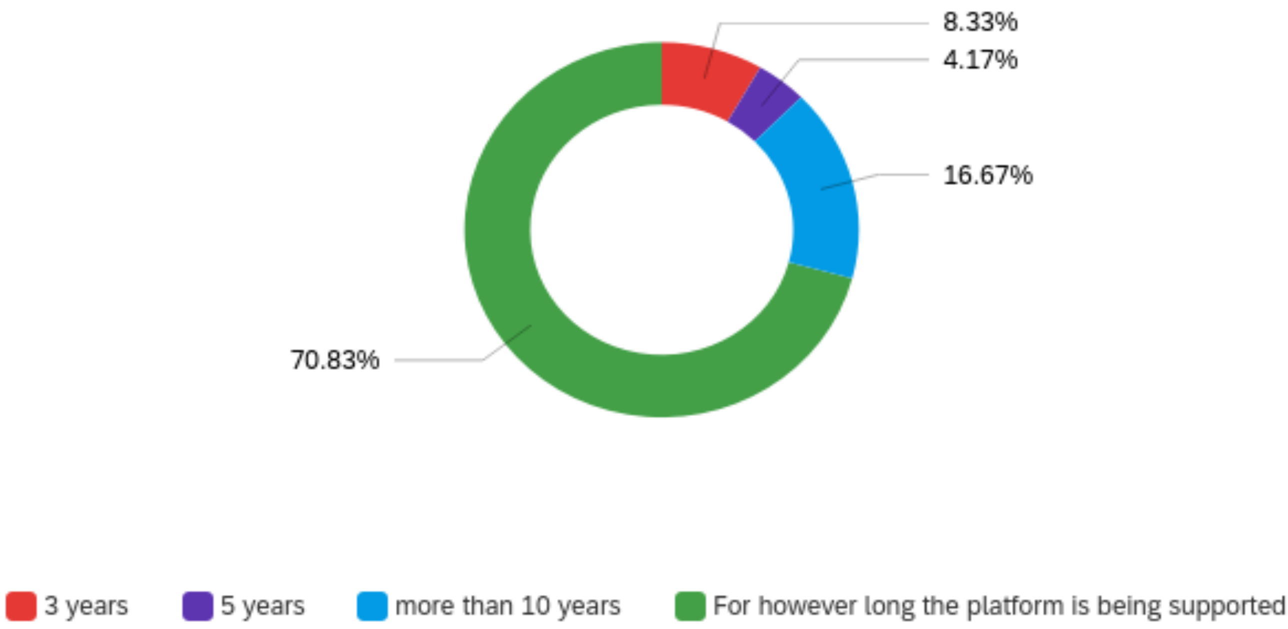
#	Field	Min	Max	Mean	Std Deviation	Variance	Count
1	Create unique identifiers (DOI) to make content searchable across the web.	3.00	5.00	4.69	0.55	0.30	48
2	Have a refined search function of the content within the platform.	3.00	5.00	4.54	0.61	0.37	48
3	Allow search engines to harvest data from the platform.	2.00	5.00	4.04	0.76	0.58	48
4	Provide licensing information	3.00	5.00	4.72	0.57	0.33	47
5	Include information on how to cite the project, objects, and/or annotations	2.00	5.00	4.77	0.62	0.38	48
6	Other	3.00	5.00	4.50	0.87	0.75	4

#	Question	Not important at all		Somewhat important		Neutral		Fairly important		Essential		Total
1	Create unique identifiers (DOI) to make content searchable across the web.	0.00%	0	0.00%	0	4.17%	2	22.92%	11	72.92%	35	48
2	Have a refined search function of the content within the platform.	0.00%	0	0.00%	0	6.25%	3	33.33%	16	60.42%	29	48
3	Allow search engines to harvest data from the platform.	0.00%	0	2.08%	1	20.83%	10	47.92%	23	29.17%	14	48
4	Provide licensing information	0.00%	0	0.00%	0	6.38%	3	14.89%	7	78.72%	37	47
5	Include information on how to cite the project, objects, and/or annotations	0.00%	0	2.08%	1	4.17%	2	8.33%	4	85.42%	41	48
6	Other	0.00%	0	0.00%	0	25.00%	1	0.00%	0	75.00%	3	4

Other - Text

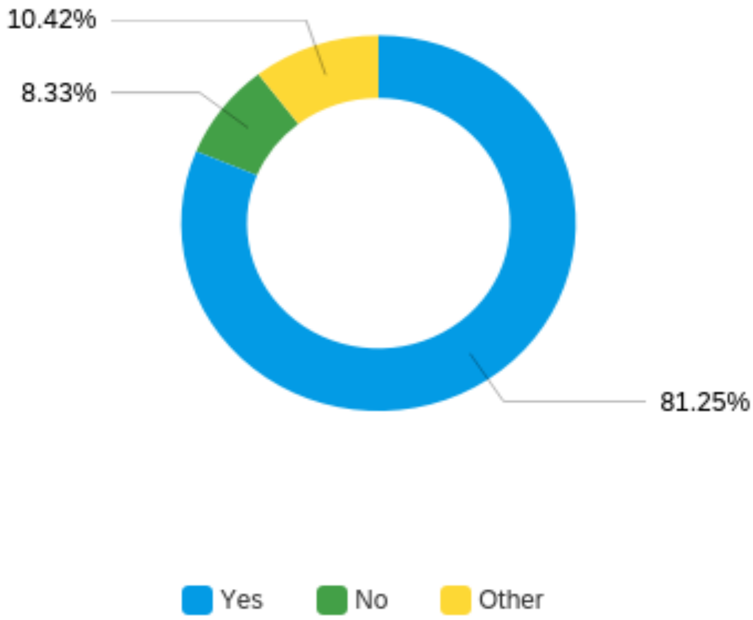
1. Allow embedding in other sites
2. DOI at the level of annotation

Q14 - It is my expectation that a free open-source repository would keep and maintain my models for a duration of...



#	Answer	%	Count
1	3 years	8.33%	4
2	5 years	4.17%	2
3	more than 10 years	16.67%	8
4	For however long the platform is being supported	70.83%	34
	Total	100%	48

Q15 - Would you include in a project's funding module the cost of perpetual care and long-term preservation?

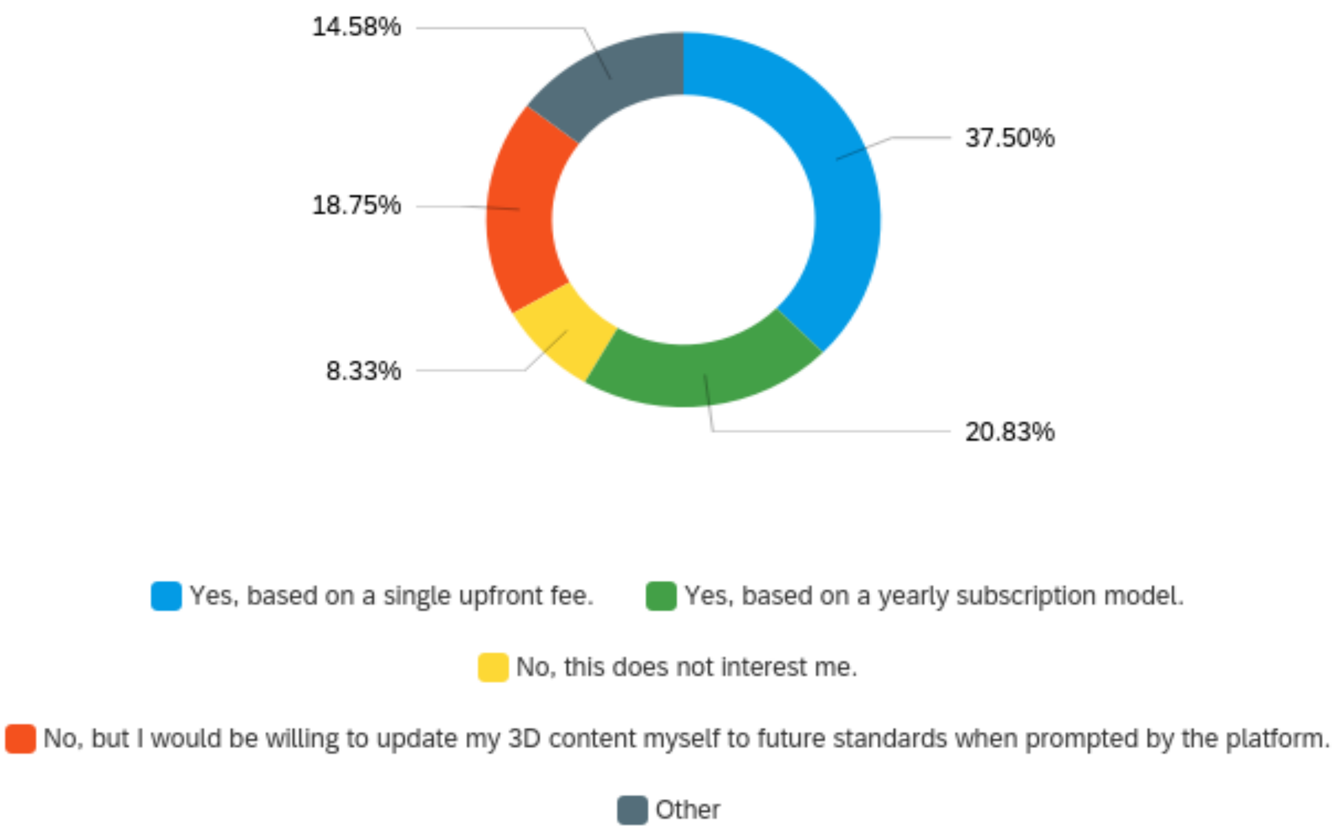


#	Answer	%	Count
1	Yes	81.25%	39
2	No	8.33%	4
4	Other	10.42%	5
	Total	100%	48

Other - Text

1. Depends on the costs
2. I would be in favor of a paid tier for longer term storage/hosting, or free if the model is shared on a creative commons license
3. If allowable, yes
4. It depends on what that cost is, and how it would be paid for -- yes if it was a one-time fee that was in proportion to the rest of the project budget
5. I don't know what a funding module is.

Q16 - With either personal funding or project funding, would you be willing to pay for perpetual care of the models?

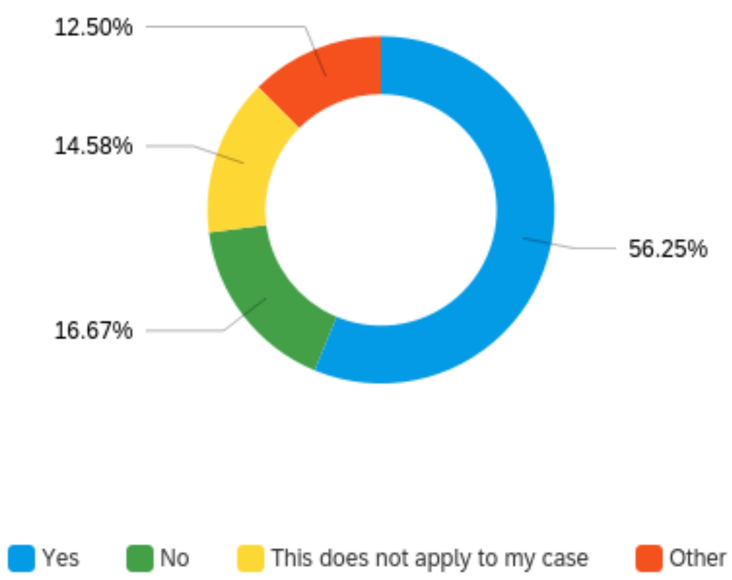


#	Answer	%	Count
1	Yes, based on a single upfront fee.	37.50%	18
2	Yes, based on a yearly subscription model.	20.83%	10
3	No, this does not interest me.	8.33%	4
4	No, but I would be willing to update my 3D content myself to future standards when prompted by the platform.	18.75%	9
5	Other	14.58%	7
	Total	100%	48

Q16_5_TEXT - Other

Other - Text
1. I would love to have a pay per view option for the creator sharing the revenue between him and related parties e.g. the project maintainers.
2. Core functionality should be integrated into existing (and funded) open research data platforms
3. Depends on the fee
4. yes but with the donation/wikipedia model
5. Any of these models are potentially of interest. My most important feature would be that the platform itself is stable long term.
6. Yes, with project funding based on a yearly or perpetual fee.
7. If I was an end user with funding, I would be open to paying either a single fee or a yearly subscription fee, depending on who was offering it and what services came with it.

Q17 - Does your organization or institution recognize and reward this type of atypical scholarly output?

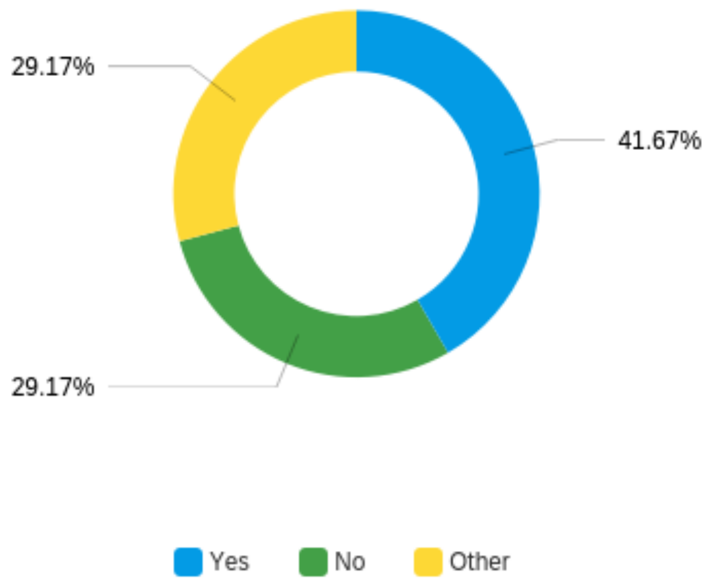


#	Answer	%	Count
1	Yes	56.25%	27
2	No	16.67%	8
3	This does not apply to my case	14.58%	7
4	Other	12.50%	6
	Total	100%	48

Other - Text

1. not sure
2. They're working on standards for this now. I expect that they will in ~3 years.
3. They do not grasp the significance of 3D modelling (although they are getting the general idea)
4. Depends on who asks for it
5. This output may be recognized on an ad hoc basis, but it is not considered scholarly output on a policy level
6. Not sure as I'm ECR and don't count for most things at my Uni!

Q18 - Should projects be peer-reviewed before being published on the platform?



#	Answer	%	Count
1	Yes	41.67%	20
2	No	29.17%	14
3	Other	29.17%	14
	Total	100%	48

Other - Text

1. Depends on the object and purpose.
2. Peer-reviewed projects should be identified
3. only if end-user is not member of a university
4. I would love for this to be an option, and to make it possible to search only peer-reviewed models. I would not want that to be the only way to upload and share, especially given the turnaround time for peer review.
5. provide the option
6. it depends on the context

7. Not as a condition of publication, but certain models could be submitted for review.
8. The content should be curated, but only so the content is relevant.
9. I'd say it depends on the mission of the platform.
10. If the projects meet the standards defined by the platform it shouldn't
11. Let creators choose if they want peer review.
12. Not necessarily, but the option is interesting and good to add
13. It depends on what stipulations the institution is making about the content and who the audience is. (young school age education, academic, or "life-long learning")