Virtual Archaeology Review, **11**(23): 1-15, 2020
https://doi.org/10.4995/var.2020.13226

Received: March 4, 2020
Accepted: May 26, 2020

SURVEY OF 3D DIGITAL HERITAGE REPOSITORIES AND PLATFORMS

ESTUDIO DE LOS REPOSITORIOS Y PLATAFORMAS DE PATRIMONIO DIGITAL EN 3D

Erik Champion, Hafizur Rahaman *

Faculty of Humanities, Curtin University, Bentley 6845, Australia. erik.champion@curtin.edu.au; hafizur.rahaman@curtin.edu.au

Highlights:

- A survey of relevant features from eight institutional and eleven commercial online 3D repositories in the scholarly field of 3D digital heritage.
- Presents a critical review of their hosting services and 3D model viewer features.
- Proposes six features to enhance services of 3D repositories to support the GLAM sector, heritage scholars and heritage communities.

Abstract:

Despite the increasing number of three-dimensional (3D) model portals and online repositories catering for digital heritage scholars, students and interested members of the general public, there are very few recent academic publications that offer a critical analysis when reviewing the relative potential of these portals and online repositories. Solid reviews of the features and functions they offer are insufficient; there is also a lack of explanations as to how these assets and their related functionality can further the digital heritage (and virtual heritage) field, and help in the preservation, maintenance, and promotion of real-world 3D heritage sites and assets. What features do they offer? How could their feature list better cater for the needs of the GLAM (galleries, libraries, archives and museums) sector? This article's priority is to examine the useful features of 8 institutional and 11 commercial repositories designed specifically to host 3D digital models. The available features of their associated 3D viewers, where applicable, are also analysed, connecting recommendations for future-proofing with the need to address current gaps and weaknesses in the scholarly field of 3D digital heritage. Many projects do not address the requirements stipulated by charters, such as access, reusability, and preservation. The lack of preservation strategies and examples highlights the oxymoronic nature of virtual heritage (oxymoronic in the sense that the virtual heritage projects themselves are seldom preserved). To study these concerns, six criteria for gauging the usefulness of the 3D repositories to host 3D digital models and related digital assets are suggested. The authors also provide 13 features that would be useful additions for their 3D viewers.

Keywords: 3D model; portals; repositories; digital cultural heritage; virtual heritage; survey

Resumen:

A pesar del creciente número de portales de modelos tridimensionales (3D) y repositorios en línea que atienden a los estudiosos del patrimonio digital, a los estudiantes y al público en general, hay muy pocas publicaciones académicas recientes que analizan de forma crítica el potencial relativo de esos portales y repositorios en línea. Tampoco hay suficientes revisiones críticas de las características y funciones que ofrecen, ni muchas explicaciones sobre la forma en que estos activos y su funcionalidad pueden impulsar en el campo del patrimonio digital (y el patrimonio virtual), y ayudar a preservar, mantener y promocionar los sitios y activos del patrimonio 3D del mundo real. ¿Qué características ofrecen? ¿Cómo podría su lista de características satisfacer mejor las necesidades del sector GLAM (galerías, bibliotecas, archivos y museos)? La prioridad de este artículo es examinar las características útiles de 8 depósitos institucionales y 11 comerciales diseñados específicamente para albergar modelos digitales en 3D. También son examinadas las características disponibles de su visores 3D asociados, cuando sea aplicable, y ello conecta con lo recomendado sobre las necesidades futuras y mejoradas para abordar las lagunas y debilidades en el campo académico del patrimonio digital 3D. Muchos proyectos no estudian los requisitos estipulados en las cartas, como son los factores de acceso, la reutilización y la preservación. La escasez de estrategias y ejemplos de preservación pone de relieve el carácter oximorónico del patrimonio virtual (oximorónico en el sentido de que los propios proyectos de patrimonio virtual se preservan con muy poca frecuencia). Para hacer frente a estas preocupaciones, se sugieren seis criterios para calibrar la utilidad de los repositorios 3D para albergar modelos digitales 3D y activos digitales relacionados. Los autores también proporcionan 13 características adicionales que serían útiles en los visores 3D.

Palabras clave: modelo 3D; portales; repositorios; patrimonio cultural digital; patrimonio virtual; estudio

* Corresponding author: Hafizur Rahaman, hafizur.rahaman@curtin.edu.au

1. Introduction

An increasing number of digital heritage infrastructures have emerged, providing an improved user experience for those visiting museums, exhibitions, archaeological sites, and various cultural places/sites. More sophisticated computer applications are emerging to support the modern demands of digital preservation, documentation, and dissemination of heritage artefacts and sites (Galeazzi & Di Giuseppantonio Di Franco, 2017). And increasingly powerful, accessible and useful 3D modelling and multimedia software (Pavlidis, Koutsoudis, Arnaoutoglou, Tsioukas, & Chamzas, 2007) has inspired a variety of hobbyist and community-generated 3D assets, available in flexible new formats with links to social media platforms.

In an ideal world these new software and hardware opportunities, along with advances in the ease, range and power to digitize, opens up new frontiers for the documentation, representation and dissemination of heritage assets (Sullivan, Nieves, & Snyder, 2017; Tucci, Bonora, Conti, & Fiorini, 2017). But there are persistent and problematic issues: securing reliable and robust 3D data based on shared, standard file formats; comprehensive and consistent metadata (Maiwald, Bruschke, Lehmann, & Niebling, 2019); information regarding the acquisition process, copyright, shareholder rights and authenticity (Muñoz Morcillo, Schaaf, Schneider, & Robertson-von Trotha, 2017) and access: the long term preservation of 3D assets and their use and reuse for scholarly purposes, student learning and wider public dissemination, and so on (Champion, 2018; Koller, Frischer, & Humphreys, 2009; Niven & Richards, 2017; Rabinowitz, Esteva, & Trelogan, 2013).

3D models and 3D spaces play a vital role in understanding and interpreting archaeology and heritage sites (Bernard et al., 2017; Cots, Vilà, Diloli, Ferré, & Bricio, 2018), so the question of whether they are copies, in a repository or a depository depends on their function, as certification, as a record, for safe-keeping and storage, or as dissemination of information (Galeazzi et al., 2018). 3D assets are important for scholarly arguments and publications, providing scientific data and evidence, but communicating their value would be helped by infrastructure that allows for critique and comparison, and infrastructure that follows the needs of the experts who develop and evaluate them.

Various heritage scholars and charters (such as the London and Seville Charters) declared the success of virtual heritage (VH) projects depend on 3D models and associated scholarly contents (Scopigno, Callieri, Dellepiane, Ponchio, & Potenziani, 2017; Tucci et al., 2017). They warned us that we need to better safeguard digital heritage in order to promote and disseminate real-world heritage knowledge.

However, the recommendations of these charters are not generally addressed by 3D digital heritage infrastructure. A recent study by Statham (2019) on five online platforms (Google Arts and Culture, CyArk, 3DHOP, Sketchfab and game engines) revealed that ICOMOS (International Council on Monuments and Sites) and UNESCO (United Nations Educational, Scientific and Cultural Organization) heritage recommendations are not the prime market drivers of commercial solutions (such as Sketchfab) and their supporting documentation is often incomplete and inadequate.

Sadly, 3D models are rarely preserved; they are too often inaccessible, their online existence and usage typically short-lived (Doyle, Viktor, & Paquet, 2009; Ioannides & Quak, 2014; Münster, Pfarr-Harfst, Kuroczyński, & Ioannides, 2016). Expensive digital heritage projects such as Beyond Space and Time, Rome Reborn and the VRML (Virtual Reality Modelling Language) 2.0 showcase SGI (Silicon Graphics, Inc) Teotihuacan model, were showcases of new technology matched with expert scholarship, now they are exemplars of lost, hidden, or obsolete digital heritage. Accuracy, authenticity, ownership rights are prominent issues, according to Di Giuseppantonio Di Franco, Galeazzi, & Vassallo (2018); Muñoz Morcillo et al. (2017); Statham (2019); and Sullivan et al. (2017).

Despite the increasing number of cultural heritage 3D models (Münster et al., 2016), along with the presence of more than 50 commercial repositories available for downloading, sharing and trading 3D models (Table 5) (Übel, 2019); a survey article by Champion & Rahaman (2019) found that 3D data reliability, robust file formats, agreed metadata, integrated paradata and accessible copyright information are problematic issues hinder the archiving and widespread dissemination of 3D heritage assets.

Champion & Rahaman (2019) have previously warned that there have been few studies and related documentation on existing 3D repositories and their features lists. More research in this area would help galleries, libraries, archives and museums (the GLAM sector), cultural heritage professionals and enthusiastic 3D modellers to better select, add to, and maintain these repositories.

Given the problems besetting 3D heritage models, the purpose of this article is to offer a critical review of popular online 3D repositories, their related services, and their specialized features for hosting and displaying online 3D cultural heritage assets. This article aims to help heritage and GLAM industry professionals in their decision-making and selection of suitable online 3D platforms.

In particular, this article addresses these questions:

- What are the existing online 3D repositories that support digital cultural heritage?
- What hosting features do they offer?
- What are the specific features of their 3D viewers?
- Which new and future features could and should be included to better support GLAM collections, heritage scholars and heritage communities?

To avoid potential confusion, this article will define four key terms which can suffer from conflicting, vague, or overlapping interpretations:

- *Repository* here means a centralized location where aggregation of data is kept and maintained in an organized way. “3D repository” here refers as a website for uploading, finding and downloading 3D models (such as TurboSquid).
- *Depository* is here defined as a location where things are deposited for storage or safeguarding.
- A web *portal* is usually a single point of access website which links to information from diverse sources, like metadata, 3D and images, in a consistent and uniform fashion. A portal can assemble disparate information from various sources

but with shared formats and an overall theme, for example, the Europeana portal[1].

- An *archive* is a collection of data moved to a repository; often the data is kept separate for compliance reasons or for moving from primary storage media[2]. Archived data is not a copy, but rather inactive and rarely altered data that needs to be retained for long periods. Archiving is typically required to store large amounts of data, for long periods at a low cost.

The next section of the article provides a brief overview of existing 3D model hosting and archiving infrastructure-based repositories and related issues that arise when using them as scholarly resources. A review of an online survey on public and commercial 3D repositories includes a detailed feature list of those repositories. We investigate and discuss potential GLAM-relevant features and conclude with recommendations to aid the further development of 3D repositories.

2. 3D file format, online viewing and publishing

Virtual heritage (VH) is commonly used to describe projects combining virtual reality (VR) and cultural heritage (Addison, 2000; Roussou, 2002). 3D models play a vital role in VH: the success of a VH project greatly depends on 3D models and their associated scholarly content (Scopigno et al., 2017; Sullivan et al., 2017; Tucci et al., 2017).

One might be led to believe that, with the dramatically increasing number of academic articles focusing on 3D digital heritage, (especially VH) that the projects and their associated 3D models are carefully and comprehensively preserved. Sadly, there is a decreasing number of accessible 3D assets (Champion & Rahaman, 2019; Thwaites, 2013). Given these figures, the field of digital heritage as a sustainable scholarly activity is problematic, for 3D models are an essential part of scholarly advances and pedagogical engagement.

UNESCO (2003) recommends developers, designers, and publishers to work with heritage organisations (such as libraries, museums, and the private sector), and professional associations and institutions and universities (and other research organisations) to preserve digital heritage data and to train and to share experience and knowledge in a "sustained" fashion. However, scholarship based on 3D digital heritage projects still lacks critical insights (Tsiafaki & Michailidou, 2015) and collaborative decision-making mechanisms (Snyder, 2014).

For example, in our recent investigations into this field of scholarship, we did not find a satisfactory number of articles or reports explaining the opportunities and potentialities for hosting and sharing 3D digital assets online; especially important for small organisations, heritage professionals and institutes and enthusiastic individuals. Many digital heritage models are neither directly linked to research projects, nor easily accessible either as interactive digital experiences or as scholarly resources.

If our aim is to help the public to understand and become more involved in VH then they should be able to understand the potential and limitations of current technology. For example, 3D components could allow annotation and editing, assets could be linked via metadata, and usage and re-usage could be tracked. However, experts and end-users must work together to ensure technology continually supports useful and relevant experiences and data evaluation.

3D online repositories can help provide these features, but there are many different platforms, features, formats, and viewers. The following sections provide a brief summary on 3D file formats, web-based 3D viewers and issues related to 3D publication.

2.1. 3D file formats

3D models have been deployed as simplified representations of reality for a long time in architecture, architectural history, archaeology and related disciplines (Kuroczynski, 2017). A 3D model can be a digital surrogate or a virtual conjectural reconstruction of a ruin, long-disappeared heritage site, or explorative simulation of missing artefacts. Expressing and respecting the values of 3D digital heritage, the 2006 London Charter (Beacham, Hugh, & Niccolucci, 2009) highlights the interpretive creative process of digital 3D reconstruction and the subsequent 3D visualization.

The content of a 3D model can be classified into three categories, such as geometry, appearance, and scene information (McHenry & Bajcsy, 2008), and their file format depends on the application for their production.

VH projects are typically composed of 3D models but preservation and extrapolation of 3D data for long-term use is still an issue (Greenop & Barton, 2014). Koller et al. (2009) identified the absence of a shared, secure and feature-rich file format for 3D models as a major obstacle. Closed or proprietary formats can also cause problems in terms of access, reliability, and longevity, and the resulting models can lack a range of desired or desirable features (Koller et al., 2009).

Many research projects and publications examine the usefulness of .OBJ, .3Ds, .u3D, .o3D, .x3D and .DAE formats, but there are also other file formats such as .UNITY, .SKP, .DXF, and .BLEND, which are popular among 3D CG (Computer Graphics) communities. A study by McHenry & Bajcsy (2008) confirms the existence of more than 140 file formats for 3D models. That does not mean all file formats are and remain popular. A recent survey by Sketchfab[3] determined that .glTF and .PLY formats are increasingly commonly used by heritage communities. While there are a bewildering number of possible 3D formats, relying on one format is also risky; it may create problems such as synchronising updates, it can also increase time and resources required for administration, maintenance, and storage space (Champion, 2018). We may also need one file format for archiving, and another simpler and smaller format for online browser-based viewing but that may also increase storage and maintenance requirements.

2.2. Online and web-based viewers

Web support for 3D content viewing stabilized well after the advent of conventional digital media, such as text,

[1] www.europeana.eu/portal

[2] https://searchstorage.techtarget.com/definition/archive, date: 31 Jan 2020.

[3] https://tinyurl.com/wnysl8d, date: 3 Mar 2020.

images, video and sound (Scopigno et al., 2017). Early approaches to publishing and visualising 3D models on the web through VRML and .x3D offered (and still offers) a free and relatively stable cross-platform environment (although VRML had many implementation issues that we will not detail here). Despite this, their functionality was and still is relatively limited: 3D data was typically restricted to a specific visualisation tool, implemented as a plugin, which had to be downloaded.

The development of the WebGL standard in 2009 (Khronos, 2009) was a significant step forward. Based on the OpenGL eco-system; WebGL is a JavaScript programming interface (API) and allows modern browsers to natively render 3D models using graphics hardware without requiring any additional extensions or plugins. Another potential way to provide online 3D visualisations is through game engines. Many contemporary game engines, such as Unity, CryEngine and Unreal, can run as standalone applications, web plugins, and across various devices, such as handheld smartphones and head-mounted displays (HMDs).

For example, 3DHOP (3D Heritage Online Presenter) is open-source software under GPL (General Public License) which creates interactive web presentations of high-resolution 3D models, oriented to the cultural heritage field (Potenziani et al., 2015). 3DHOP is based on WebGL, a subset of HTML5, it performs well in most modern browsers without requiring a plugin. However, it supports only .PLY and Nexus (.NXS or .NXZ) file formats. For single resolution 3D models (small geometry and less than 1 MB of file size), the suggested file format is .PLY. However, only one texture image (PNG & JPG) is supported for this file type. 3DHOP suggests the Nexus file format for multi-resolution 3D models (1~100 million triangles/points). Multiple texture images (PNG & JPG) are possible with Nexus (while 'per-vertex colour' is supported by both .PLY and Nexus formats).

Universal Viewer[4] (UV) is also worth mentioning. UV is a community-developed open-sourced project. Developed by Digirati[5] in 2012 as the 'Wellcome Player' for the British Library of Wales, it supports rich multimedia for presentation of Deep Zoom images, audio, video and PDF assets, with search, bookmarking, downloads and other features. The player was later generously open sourced on GitHub by the Wellcome Library.

From 2014 UV started supporting the IIIF (International Image Interoperability Framework) specifications in order to serve images in a similar fashion via a simple web server. It also displays various media files and 3D models, as long as the appropriate extension is installed. Since the adoption of IIIF, UV has been adopted by various institutions and has a growing community of contributors and adopters, including Omeka[6].

2.3. 3D in publications

PDF (portable document format) is a popular and relatively secured way for publishing digital scholarly articles with embedded 3D models. However, PDFs have limited interactivity and cannot provide a rich sense of spatial immersion. When 3D models are embedded inside a PDF they are usually not dynamically linked to any scholarly information (i.e. metadata and paradata). However, there have been recent attempts to embed more dynamic models through either introducing specific viewers such as U3D (Universal 3D) (Zhang, Li, Jia, Zhang, & Liu, 2017) or applying open-source tools (based on MeVisLab imaging framework) (Newe, Brandner, Aichinger, & Becker, 2018).

Despite some recent attempts, VH models are still not commonly accessed via online publications (Aalbersberg, Cos Alvarez, Jomier, Marion, & Zudilova-Seinstra, 2014). Realising the need to reference 3D data in an academic publication, a few publishers have started to provide viewable 3D content in online publications (such as *Digital Applications to Archaeology and Cultural Heritage* and *Studies in Digital Heritage)*.

In general, this is usually provided in one of two ways. Either the publisher hosts the 3D assets, and viewing is facilitated through their in-house developed tools, such as Elsevier's *3D molecular viewer* and *3D archaeological viewer*[7]. Or, the publishers embed a third-party viewer in their online publication, and the 3D model is hosted by the third party as well. For example, Taylor and Francis accept 3D models hosted only at Sketchfab[8] and uses Sketchfab viewer in their online journals to display and showcase the model[9].

This is not only an academic journal issue. We rarely find online and library accessible depositories for VH models, and many academic research projects lack long-term infrastructure and preservation strategies (Champion, 2019). Due to the scope of this article, we have limited our study to online 3D repositories and platforms only, and have excluded journals.

3. Repositories

3D documentation of cultural heritage is of particular importance for historic preservation, tourism, education and dissemination of cultural values (Clarke, 2015; Kiourt, Koutsoudis, Markantonatou, & Pavlidis, 2016). Despite an increasing number of 3D models (Munster, 2018), there are few online libraries and accessible depositories for VR-ready 3D models. However, the recent concerns and associated actions of EU and North American initiatives in creating archives and digital heritage infrastructure is notable, as is the existence of more than 50 commercial repositories for 3D models for downloading, sharing or exchange (Übel, 2019).

For a better understanding of these repositories and their offered supports in hosting and model viewing; this article has conducted a comparative study of 8 popular institutional and 11 commercial repositories. The survey lists basic 3D model hosting features offered by the repositories, including the associated hosting fees, supported file formats, level of accessibility, upload and download limits, model display options and the number of 3D models hosted (Tables 1 and 3).

[4] https://universalviewer.io

[5] www.digirati.com

[6] https://omeka.org

[7] https://www.elsevier.com/connect/ bringing-3D-visualization-to-online-research-articles, date: 01 Nov. 2019.

[8] http://sketchfab.com

[9] https://authorservices.taylorandfrancis.com/3D-models, date: 01 Nov. 2019.

The digital heritage domain is rich and complex (Scopigno et al., 2017). GLAM and cultural heritage professionals use different types of visual media in their study, analysis and interpretations. The 3D model is one of the most important media types to document and display the status and value of cultural heritage assets. Once we can ensure archiving and access to the 3D data, the next step should be to evaluate the visibility and exhibition capability of the hosting site.

Sullivan (2016) and Calin et al. (2015) suggested a real-time viewer which can display a dynamic model and allows the researcher to rotate and shift their viewing position. Sullivan & Snyder (2017) also emphasised the human experience of meaning-making and suggested 3D model navigation (at pedestrian level) and real-time interaction are important tools for scholarly understanding. Pauwels, Verstraeten, De Meyer, and Van Campenhout (2008) suggested typological annotations and visualisation of changes in a building or its component through time. Statham (2019) also emphasised the usefulness of annotation and related tools to support scientific rigour.

Regarding the design of a 3D visualisation supported by a web-based platform, Boutsi, Ioannidis, and Soile (2019) suggested focusing on: the graphics user interface (GUI), dynamic multimedia annotation, dynamic rotation of camera movement and clickable labels. Galeazzi & Di Giuseppantonio Di Franco (2017) pointed out human-object interaction is an important aspect of 3D visualisation and argued we should link various datasets and provide suitable, useful access to researchers and practitioners. Alliez et al. (2017) however, recommend providing the full data resolution of the 3D model, dynamic lighting, measuring features, non-photorealistic lighting, cut-through sections, maps and sections from the 3D model, a dynamic camera, volume calculation at different layers, exploded views, space wrapping for enhanced visibility and inspection, including an option for transparent rendering.

Champion (2019) on the other hand suggested a relatively inclusive list of features which a 3D viewer could support for more useful VH experiences. Adopting his suggestion (which is also corroborated by digital heritage scholars such as Sullivan et al. (2017), Sullivan & Snyder (2017), and Koller et al. (2009)) this article reviewed these repositories and listed their 3D model viewing functionality and display features suitable for web-archiving and online publication.

Features offered by the '3D model viewer' include: zooming and rotation capabilities; walking around and inspecting the digital model; adding/removing components; changes to the presented mesh in terms of wireframe or texture view; being able to take screenshots; annotation of text/image; measurement tools; and the ability to download file formats:

- Zoom in, zoom out and rotate the model 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. Allowing removing/adding parts of the 3D model (as components, area, layers or in terms of authenticity) may help virtual reconstruction of a conjectural model and online collaboration.
- Wireframe and texture view; allowing the user to view the 3D model under various viewing conditions (solid, shaded etc.)
- Taking screenshots. While focusing on a certain perspective or zooming on specific detail the 3D viewer allows the user to take screenshots of the view.
- Allow user to annotate information or media (text, image, sound etc.) with the 3D model.
- Can pose and change the field of view. Thus, helping the users to view the 3D model/space from various perspectives/angles/locations.
- Measuring the 3D model is an important feature which helps the scientific investigation. Hence, the 3D viewer should allow measurements of various parts of the 3D model.
- The range of file formats allowed for downloading by the repository is another important feature. Some repositories allow online file conversion; as well as downloading a 3D model in its native format.
- Can the platform work with timelines, so that the model shows changes over time? This is a helpful feature for archaeological research.
- Embedding a 3D model in an external webpage or within a scholarly publication is important for accessible cultural heritage dissemination and scholarly argument. It is important to know whether the repository facilitates direct embedding (or just provides a web link).

DOI (digital object identifier) ensures the international standardization of a scholarly article and permanently identifies content[10]. Similarly, DOI assigned to a digital object may provide unique identity and can be cited/refer easily. Inclusion of DOI or similar supports and options for embedding 3D model to other media have been checked as well, and the observations are presented in Tables 2 and 4.

3.1. Institutional and non-commercial repositories

In general, institutional repositories do not allow the general public to upload 3D content. Instead, they offer free services with unlimited downloads but file formats are restricted. In some cases (such as CARARE) 3DPDF are allowed, which embeds a 3D model inside a PDF. However, due to the vulnerability and security issues associated with PDF, and to increase support for low-end browsers running on mobile devices; it seems that newer publishing techniques based upon HTML5 and WebGL are becoming popular alternatives (for instance, CARARE Pro) (Pletinckx & Nolle, 2015).

It can be very difficult to find specific 3D models and related information, the majority of 3D models are not connected to external sites or portals. Below is a simplified list:

- For example, the Smithsonian offers 3D displayed models but does not clarify how they were used or explain related cultural protocols; and does not provide full archival records or external resource links (Champion, 2018).

[10] https://www.ijser.org/Benefits-of-doi.aspx, dated 28 Jan 2020.

Table 1. Non-commercial institutional repositories - 3D hosting features offered (selective).

	Smithsonian http://3d.si.edu	**Three D Scans** http://threedscans.com	**CyArk** http://cyark.org	**Europeana** http://europeana.eu/portal/en	**EPOCH** http://epoch-net.org	**CARARE** http://pro.carare.eu	**NASA 3D Resources** https://nasa3d.arc.nasa.gov	**GB3D Type Fossils** http://3d-fossils.ac.uk/home.html
General features								
Fees	Free	Free	Free, require prior application	Free	Free	Free	Free	Free
Supported formats	STL, OBJ, .blend, .f3z, f3d, .USDZ, Single ASCII point cloud	OBJ, STL	LiDAR, point cloud, photogrammetric imagery	JPEG, GIF, PNG, PDF, Plain ASCII, MP3, MPEG, AVI, FBX, MTL, OBJ, WRL	PDF	PDF, 3D PDF	STL, 3DS	PIY, OBJ
Accessibility/ use	With few exceptions offers access to the data sets	No copyright restrictions	Licensed under a Creative Commons Attribution-Non-commercial 4.0 International License	Databases/assets are hosted by external contributors	Not known	Not known	Non-Commercial Use only	Creative Commons Attribution Non-commercial Share Alike 3.0 Unported License.
Max file size/ download limit	Download limit is not known	Unlimited	Varies, prior permission required	Not known	Unlimited	Unlimited	Unlimited	Not known
Model display	3D	2D, 3D, animated gif	2D, 3D	2D, 3D	2D	3D inside PDF	2D	
Hosted model	Not known	Not known	200+ sites	50 million+ items, 3D not known	Not known	Not known	324 models (30 Jan 2020)	1800 3D scans

Table 2. Non-commercial institutional repositories-3D model viewer features offered (selection).

	Smithsonian http://3d.si.edu	**Three D Scans** http://threedscans.com	**CyArk** http://cyark.org	**Europeana** http://europeana.eu/portal/en	**EPOCH** http://epoch-net.org	**CARARE** http://pro.carare.eu	**NASA 3D Resources** https://nasa3d.arc.nasa.gov	**GB3D Type Fossils** http://3d-fossils.ac.uk/home.html
3D model viewer features								
Zoom/rotate	Yes	No	No	Depends on the host	Site partly down (30 Jan 2020)	Yes	No	Yes
Walk around	No	No	No	-	-	Yes	No	No
Add/remove parts	No	No	No	-	-	Yes	No	No
Wireframe/ texture view	Yes	No	No	-	-	Yes	No	Yes
Take screenshots	No	No	No	-	-	No	No	No
Annotations	Yes	No	No	-	-	Yes	No	No
Can change field of view	No	No	No	-	-	No	No	No
Measure	Yes	No	No	-	-	Yes	No	No
Import/export options	No	No	No	-	-	No	No	No
Change timelines	No	No	No	-	-	No	No	No
DOI provided	No	No	No	Yes	-	No	No	No
Embeddable	Yes	No	No	Yes	-	No	No	No

Table 3. Non-commercial institutional repositories-3D model viewer features offered (selection).

	Sketchfab https://sketchfab.com	**MyMiniFactory** https://myminifactory.com	**Blendswap** https://www.blendswap.com	**3D Warehouse** https://3dwarehouse.sketchup.com	**TurboSquid** https://turbosquid.com	**ShareCG** https://sharecg.com	**3DExport** https://3dexport.com	**Free3D** https://free3d.com	**Unity Asset Store** https://assetstore.unity.com	**Poly** https://poly.google.com	**p3d.in** https://p3d.in
General features											
Fees	Various subscriptions, discounted fees for education & museum	Free and paid	Free	Free	Free and paid	Free	Free and paid	Free and paid	Free and paid	Free	Free and paid
Supported formats	50 file formats	54 file formats	37 file formats	.SKP	16 file formats	47 file formats	16 file formats	14 file formats	FBX or OBJ	OBJ, glTF, GLB	OBJ, MTL, GLTF, GLB
Accessibility /use	Creative Commons licensing. Upload varies on membership	Model Licenses: Various	Varying Creative Commons	General Model License Agreement	Model Licenses: Various	Creative Commons BY-NC-ND License	Basic and Extended License	Model Licenses: Various	Model Licenses: Various, Asset Store EULA.	Published under a CC-BY 3.0 license	Limited, non-exclusive license to access and use
Max file size/ download limit	Basic-50MB, Pro-200MB, Premium-500MB, Business-unlimited	Unlimited uploads	Free 90MB upload and 200MB download	50MB (max) upload	No limit	180MB	500 MB	Not known	4GB (max) upload. Unlimited download	100MB	100MB~4GB for Basic. 6GB+ for PLUS
Model display	2D, 3D, AR, VR	2D	2D	2D, 3D	2D, 3D	2D	2D	2D	2D	2D,3D	2D,3D
Hosted model	3 million models (200000 free models), 100000 CH models (28000 downloadable)	76287 published, printable objects (30 Jan 2020)	21975 models (30 Jan 2020)	Not known	820048 models (30 Jan 2020)	9550 models (30 Jan 2020)	169298 models (30 Jan 2020)	225250 models (30 Jan 2020)	Not known	Not known	Not known

Table 4. Commercial repositories-3D model viewer features offered (selection)

3D model viewer features	Sketchfab https://sketchfab.com	MyMiniFactory https://myminifactory.com	Blendswap https://www.blendswap.com	3D Warehouse https://3dwarehouse.sketchup.com	TurboSquid https://turbosquid.com	ShareCG https://sharecg.com	3DExport https://3dexport.com	Free3D https://free3d.com	Unity Asset Store https://assetstore.unity.com	Poly https://poly.google.com	p3d.in https://p3d.in
Zoom/Rotate	Yes	No	No	Yes	No	No	No	No	No	Yes	Yes (auto rotate)
Walk around	Annotated points	No	No	No	No	No	No	No	No	No	No
Add/remove parts	No	No. Remixed allowed.	No	No	No	No	No	No	No	No. Remix allowed.	No
Wireframe/ texture view	Yes	No	No	No	No	No	No	No	No	No	Yes
Take screenshots	Yes	No	No	No	No	No	No	No	No	No	No
Annotations	Yes	No	No	No	No	No	No	No	No	No	No
Can change field of view	Yes	No	No	Yes	No	No	No	No	No	No	No
Measure	Yes	No	No	No	No	No	No	No	No	No	No
Download options	Native format, glTF, USDZ	STL		Sketchup, Collada	Native format, Free format conversion	Native format	Native format, Free format conversion	Native format	Unity	FBX, glTF. OBJ, USDZ	OBJ, glTF, GLB (PLUS members only)
Change timelines	No	No	No	No	No	No	No	No	No	No	No
DOI provided	No	No	No	No	No	No	No	No	No		No
Embeddable	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes

Table 5: Commercial repositories/platforms from Europe and North America.

No.	*Name*	*Web link*	*Location*
1	3D Scanstore	http://www.3dscanstore.com/	UK
2	3DContentCentral	https://www.3dcontentcentral.com/	USA
3	3Delicious	http://3delicious.net/	Uzbekistan
4	3DExport	https://3dexport.com/	USA, Hong Kong
5	3Dheadscans	https://3dheadscans.com	USA
6	3dMdb	https://3dmdb.com	USA
7	3DModelFree	http://www.3dmodelfree.com	China
8	3dshook	http://www.3dshook.com	Israel
9	3dsky	https://3dsky.org	Not known
10	3dxo	https://www.3dxo.com/models	Germany
11	All3dfree	https://www.all3dfree.net	USA
12	ArchibasePlanet.com	https://archibaseplanet.com/download/5e94d9d5.html	Uzbekistan
13	Archive 3D	https://archive3d.net	Not known
14	Artec 3D	https://www.artec3d.com/3d-models	Luxembourg, USA, Russia
15	Artist-3D	http://www.artist-3d.com/free_3d_models/01architecture_pictures.php	Not known
16	Autodesk Online Gallery	https://gallery.autodesk.com	USA
17	bentanji	https://www.bentanji.com/	Italy
18	BiblioCAD	https://www.bibliocad.com	Argentina
19	Bitgem	https://shop.bitgem3d.com	Victoria, Australia
20	Blendswap	https://www.blendswap.com/	USA
21	CADNav	http://www.cadnav.com/3d-models/	USA
22	CGTrader	https://www.cgtrader.com	Lithuania, USA, Israel
23	clara.io	https://clara.io	Canada
24	craftsmanspace	https://www.craftsmanspace.com/free-3d-models	USA
25	Cults 3D	https://cults3d.com/en	France
26	Design Connected	https://www.designconnected.com/	Bulgaria
27	Dimensiva	https://dimensiva.com	Moscow, Russia
28	Evermotion	https://evermotion.org/downloads	Poland
29	FlyingArchitecture	https://flyingarchitecture.com/	Czech Republic
30	Free3D	https://free3d.com	USA
31	free3dbase	https://free3dbase.com/	Poland
32	gCreate	http://www.gcreate.com/free-3d-models	USA
33	GrabCAD	https://grabcad.com	USA, UK, Estonia, Israel
34	Hum3D	https://hum3d.com/free/	Cyprus
35	Human Alloy	https://humanalloy.com	The Netherlands
36	Kenney	https://kenney.nl	The Netherlands
37	luxxlabs	https://luxxlabs.com	UK
38	MyMiniFactory	https://www.myminifactory.com	UK
39	NASA 3D Resources	https://nasa3d.arc.nasa.gov/models	USA
40	OpenGameArt	https://opengameart.org/art-search-advanced?keys=&field_art_type_tid%5B%5D=10&sort_by=count&sort_order=DESC	Not known
41	Oyonale	http://www.oyonale.com/modeles.php?lang=en	France
42	p3d	https://p3d.in	USA

43	PARTCloud.net	https://b2b.partcommunity.com/community/partcloud/	Germany, Austria, Croatia France, Italy, UK, USA, Japan, China, South Korea, India
44	Pinshape	https://pinshape.com	Vancouver, Canada
45	PixelLab	https://www.thepixellab.net/freebies	London, UK
46	Poly	https://poly.google.com	USA
47	Renderpeople	https://renderpeople.com/	Germany
48	ShareCG	https://www.sharecg.com/b/5/3DModels	USA
49	Sketchfab	https://sketchfab.com	USA, France
50	Smithsonian 3D	https://3d.si.edu	USA
51	Syncronia	https://www.syncronia.com/	Italy
52	Thingiverse	https://www.thingiverse.com/	USA
53	TinkerCAD Things	https://www.tinkercad.com/things/	USA
54	TraceParts	https://www.traceparts.com/	USA, China, Brazil, EU
55	TurboSquid	https://www.turbosquid.com	USA
56	Unity Asset Store	https://assetstore.unity.com	USA
57	vizpark	https://www.vizpark.com/	Germany
58	Wild3D	https://wild3d.com/hosting	California, USA
59	Xfree3D	https://vwartclub.com/?section=xfree3d	Cyprus
60	YouMagine	https://www.youmagine.com/	The Netherlands

- Europeana, on the other hand, offers search by media type and links the search results to external hosting sites.
- CyArk, with its Open Heritage Program (launched in April 2018), allows free access to high-resolution 3D data (point cloud and photogrammetric imagery) of cultural heritage sites (70 data sets at the time of writing). However, users need prior permission to download 3D data.
- ThreeDScans[11] hosts impressive 3D models scanned from various museums located in Cyprus, France and UK and offers free download and use.
- Similarly, NASA 3D and GB3D share much of their collections for free for non-commercial uses.
- There are more than 20000 downloadable 3D models are shared by various museums and heritage institutes at Sketchfab[12]. Sketchfab is a commercial platform and it is discussed in the next section of this article.

One might assume that displaying 3D in a 3D viewer is commonly available on specialized 3D model hosting sites, portals and repositories. But 3D viewers are not commonly found at either institutional or commercial repositories. As Scopigno et al. (2017) noted, the delayed delivery of 3D content through the web has meant providing a suitable 3D model viewer is still a work in progress for many hosting sites. For example, EPOCH, NASA3D and GB3D hosts a large amount of 3D assets and allow unlimited downloads. However, they do not, at the time of writing, offer a 3D viewer, and users have to rely on a 2D image preview window before downloading any 3D content.

Despite the recent development of WebGL, OpenGL, 3DHOP, Universal Viewer and other related technologies; cultural organisations like the Smithsonian still depend on a third-party 3D model viewer (i.e. Autodesk viewer), which is not always browser-compatible and often resource hungry. Users with low-end PCs or PCs with limited graphics hardware may face performance issues when viewing these hosted 3D models.

Sometimes 3D models are hosted on external sites (such as for Europeana; Church of Panagia, hosted at STARC repository) but the model viewer of the originating site may not allow texture rendering, only zoom or rotation of the 3D model. The 3D viewers of most institutional/non-commercial repositories offer a few more options, typically limited to zoom, rotate, wireframe view, texture view, annotation, measure and embedding.

Interestingly, none of them offer the option to take screenshots of a model from a user-defined viewpoint or angle, allow the user to change the field of view, change the timeline of the model, or change to a specific view, component or stage of a 3D model at a required chronological period, which would be useful for history and heritage scholars. Nor are these 3D models usually linked to relevant collections. For example, in regards to the Europeana portal, this study did not uncover any initiatives from the related repositories to assign a DOI to any of their 3D assets.

3.2. Commercial repositories

Commercial repositories, on the other hand, are mostly developed with the primary objective to offer a platform to trade 3D models, and they rarely focus on

[11] http://threedscans.com

[12] https://sketchfab.com/blogs/community/over-100000-cultural-heritage-3D-models-on-sketchfab, date: 28 Jan 2020.

preservation. Because of their business model, they charge fees on trading 3D assets and are unlikely to be interested in non-profit archiving support. Therefore, their archiving policy is difficult to find in their online portal.

There is a notable exception, although a commercial hosting service, Sketchfab offers a free professional account and service, with unlimited uploads (with a monthly upload cap) for cultural heritage institutes. Participatory museums and heritage institutes can curate and exhibit their digital collections on a dedicated museum page[13].

Commercial repositories demonstrate the potential for innovative file formats (e.g. Blendswap), online support for file conversion (e.g. TurboSquid, 3DExport), and they can handle large amounts of traffic (e.g. the Unity asset store). Additionally, they provide consistent file formats and protocols, and their 3D models are usually easier to find and access. However, in most cases, these commercial repositories lack data provenance and metadata, and user-access varies according to membership level (governed by access and by payment of webhosting fees).

Hosting 3D models without providing a 3D viewer also occurs in commercial repositories. A large number of commercial platforms do not offer any 3D viewer for their users, including well-known products, such as the Unity Asset Store. Options such as 'walking around' the model (supported, for instance, by CARARE and Sketchfab) is rarely made available here. Although Sketchfab provides annotation-based changes in the provided viewing position, which also gives some impression of movement around a 3D environment.

Most of the 3D viewers that are available offer features for retrieving links and codes for embedding the model via external sites. However, none of the studied repositories offers a way to measure the model (or part of the model), or view the model across periods. On the other hand, some features are highly useful: for example, MyMiniFactory guarantees that their models are 3D printable. And Sketchfab offers annotation of text and sound, animation, ground shadows and hi-res textures, placing them in a favourable position compared to their competitors. Still, a dedicated Digital Object Identifier (DOI) is not common, let alone at a sub-site or sub-building level. One exception to this general rule is p3D, which offers a URL (Uniform Resource Locator) with a unique encrypted ID for each 3D model it hosts. Similarly, Sketchfab provides an UID or unique ID for each model with a long string of unique chracters at the end of the URL.

3.3. Discussion: 3D models, online exhibition and desirable features

Despite the many articles published in 3D projects, 3D models are missing in action, and it is challenging to find a fool-proof way to preserve 3D assets (Rahaman & Champion, 2019). A handful of scholarly articles do share their concern about digital preservation and related issues of 3D models. However, it is still rare to find studies that showcase and explain issues related to delivering and exhibiting 3D models on the web.

A user study conducted by Lloyd (2016) on Sketchfab focused on only the 'contextualisation' issue. A majority of the users appreciated Sketchfab's annotation feature and mentioned that it helped them to understand and contextualise the 3D artefacts. Echoing Lloyd's (2016) study, Statham (2019) suggests that we should present extended information to support 3D visualisation of online heritage assets, and proposes 17 considerations for an 'information package'. There are other preliminary studies, from Guidazzoli et al. (2017), Scopigno et al. (2017), Koller et al. (2009), Champion (2018, 2019), Flynn (2019) and Clarke (2015). However, these studies are not comprehensive, they do not provide clear guidelines for the target market: the GLAM sector (plus related communities and hobbyists) to showcase their 3D digital assets.

Some notable initiatives have taken place in North America and Europe, where there exist more than fifty commercial repositories/platforms for trading and sharing 3D models. However, it is still difficult to find 3D models in institutional repositories, as they typically do not link to external sites or portals. Commercial repositories provide some consistent formats and protocols, and their 3D models are increasingly easier to find and to access. Nevertheless, most of these portals (both commercial and non-commercial) fail to provide related information and resource links for further study and use. The commercial model repositories, such as ShareCG, TurboSquid, CG Trader and Yeggi, typically lack data provenance and metadata.

Surprisingly, a dedicated 3D model viewer is not supported by most of the repositories. In most cases, users can only view 2D images before deciding to download a model. It seems that institutional repositories are not keen to showcase their digital assets in 3D; even if they are supported by big names such as CyArk (supported by Google) and NASA3D (supported by NASA). Alternatives to 3D model viewers include 3D PDF (e.g. CARARE) and animated GIF (e.g. Three D Scans), but, as we mentioned earlier, they do not provide a sense of spatial immersivity, even though spatial immersivity may help to learn (Huk, 2006).

Unfortunately, there are also few commercial repositories which support a 3D viewer. Sketchfab and p3D appear to have the most comprehensive and robust 3D model viewers. Sketchfab supports annotation of text, images and web links to the model as well, an especially useful feature for heritage scholars.

Measuring 3D models is important for archaeologists, art historians, architects and built heritage practitioners, and the desirability of this feature has also been identified by Sketchfab's recent survey. Thankfully, this feature is offered by the Smithsonian portal (via their Autodesk viewer) and by CARARE (via 3D PDF). However, except Sketchfab none of the commercial 3D viewers allow users to measure their 3D model.

Surprisingly, neither institutional nor commercial repositories support viewing the 3D model over changing timelines. 3D models exist but a change in material, time, space and use, and timeline-related model information can be highly useful to scholars.

And though there is increasing concern among heritage scholars about the authenticity and protecting rights of

[13] https://sketchfab.com/museums, date 13 Nov 2019.

digital reproduction (Di Giuseppantonio Di Franco et al., 2018; Galeazzi et al., 2018); apart from Europeana, Sketchfab and P3D we cannot find similar initiatives for assigning unique IDs or DOIs to the hosted 3D digital model (which would help protect copyright and ownership).

4. Conclusion

We have surveyed and compiled data from eight institutional and eleven commercial repositories which are specifically designed to host 3D digital heritage models. Despite the increasing demand for 3D digital models and related functionality, we found the institutional repositories and portals lacked a range of useful features in the scholarly field of 3D digital heritage (and VH), and these features were also not often provided by the commercial sites. We recommend that these sites consider offering:

- Measurement tools.
- The ability to add a DOI to 3D models (and 3D subcomponent assets if feasible).
- The ability to link to archival records (and links for sharing and citing via social media).
- More reliable methods to track site traffic, online and offline usage (where possible).
- More comprehensive and useful metadata.
- A specialized and integrated 3D model viewer.

Acknowledgements

We would like to thank Thomas Flynn, Cultural Heritage Lead at Sketchfab, for feedback on a draft of the paper.

Note

The authors take responsibility for any errors or information that is superseded at the time of publication (due to the fast-changing nature of the field).

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