3D Imaging in Museums

Visa Immonen and Ismo Malinen

Abstract

In this chapter we give an overview of technological issues related to 3D modelling in museums, but also discuss the broader impact that digitalisation has on collections, research and public engagement. Although the technology for 3D digitisation of heritage sites and objects has been available since the 1990s, it is only in the 2010s that its use has boomed. This development has received institutional support by, e.g., the European Commission and the Finnish Ministry of Education and Culture. Through the 3D modelling of museum objects, the primarily public institutional set-up of cultural heritage becomes integrated into both commercial and non-commercial international platforms. In museums, 3D modelling is typically used to create accurate and widespread documentation of heritage objects, conducting novel academic research and enhancing public engagement. Much of the published work on 3D modelling of heritage focuses on describing and developing a technological framework. Nonetheless, from the point of view of heritage work, the most important issues are related to the selection of the museum objects for digitising and the use of the models in heritage institutions.

Keywords: 3D digitisation, digital workflow, heritage sites, metadata, museum collections

Technical Issues and Heritage Discussions

The documentation of archaeological and other heritage sites with 3D modelling began in the 1990s, and the first digital models of museum objects were created in the latter part of the decade. One of the earliest and best-known ventures was the Digital Michelangelo Project in 1998–1999 (Levoy et al. 2000). It scanned ten sculptures made by the Renaissance master and produced such precise models that tool marks on their surfaces could be examined. In spite of the technology being available, however, 3D modelling had its breakthrough in museums only once the technology gained more of a foothold in other venues of modern life, becoming less expensive in the latter part of the 2010s. In Finland, this development culminated in 2018 when the Ministry of Education and Culture started granting special subsidies for the 3D digitisation of museum collections. The European Commission expressed similar official interest by producing the Declaration of Cooperation on Heritage Digitisation, signed in spring 2019. The declaration stressed the importance of 3D digitisation and launched a pan-European initiative for the 3D digitisation of heritage artefacts, monuments and sites (European Commission 2019). The European Union is

also investing in many projects, which develop 3D modelling of heritage or are based on applying the technology.

Although setting up and using the technological framework of 3D modelling remains an important concern for museums, more and more emphasis is now placed on questions specific to museums and heritage, such as what museum items are chosen for digitisation, in what ways the results are made available to different audiences and how 3D models affect the experiencing of museum objects and heritage in general. Diane Zorich (2018, p. 75) argues that museums tend to digitise in "a way that reflects the past", but the actual challenge is to digitise in a way that is oriented to the future. In this chapter we give an overview of technological issues related to 3D modelling in museums, but also discuss the broader impact that digitalisation has on collections, research and public engagement.

The technology of 3D modelling was not specifically created for heritage institutions, and its advancement takes place largely outside museums. Global giants such as Apple, Google and Nokia, as well as the video game industry, invest huge sums in developing digital technology, while its use is gaining more and more importance in the construction, design, entertainment and health industries, as well as in the visual arts (Ahlavuo et al. 2016). Subsequently, the technology is commercially ingrained, from the basic tools of digitisation to making the results available and accessible online. Although Nanna Bonde Thylstrup (2018, pp. 5–6) writes of the mass digitisation of cultural heritage, such as the scanning of books, her remark that through digitalisation the primarily public institutional set-up of cultural heritage becomes integrated into international commercial platforms is also applicable to the 3D modelling of museum objects. This technology brings with it a multiplicity of interests, including the processes of standardisation and globalisation, which was previously not necessarily well recognised in cultural heritage institutions. These processes have to be faced and negotiated within museums and heritage settings.

Before Starting 3D Modelling Activities

In museums and the heritage sector, 3D modelling is seen as one of the key solutions for documenting, analysing and presenting cultural heritage. The term refers to the use of computer-based tools to capture and represent physical objects in virtual space, allowing a free manipulation and rendering of the model (Dey 2018, p. 5). 3D modelling constitutes a form of documentation which, when done correctly, does not cause any damage to the digitised items. Here, we concentrate mostly on 3D modelling of museum objects and other heritage collections. Besides objects, however, monuments and sites like buildings, archaeological remains and other immovable tangible heritage are usually key priorities for 3D digitisation. For instance, according to the European Commission's (2020) basic principles for 3D digitisation, it "is a necessity for tangible cultural heritage at risk, for preservation and restoration purposes; 3D digitisation can provide

virtual access to cultural heritage that is difficult to access or inaccessible, e.g., underwater".

Converting collections into virtual objects offers much more than just digital 3D copies of original artefacts. The 3D model produced is something other than the physical object; it is a representation, or rather a digital surrogate of the museum artefact (Häyrinen 2012, pp. 19–21, p. 24). Not only has the physical appearance of the object been transformed into digital data, some parts of the model are always created by software and, depending on the original artefact or site and its level of complexity, the dataset never covers all of the aspects of the original object. On the other hand, as an entity of the virtual realm, a 3D model is not subject to the physical and temporal constraints of its material counterpart, such as inhabiting only one location in the physical world.

In museums, the purposes of modelling usually fall into one of three major categories. Firstly, as an accurate and pervasive means of documentation, 3D models help in the preservation and conservation of physical artefacts (Fay-Leino 2016). Secondly, they allow new ways of conducting scholarly research on collections and sites. Thirdly, 3D models offer novel opportunities for public engagement in exhibitions, at heritage locations and online.

Despite the advances in digital technologies, 3D modelling is still a very time- and labour-intensive undertaking. Compared with traditional photography, it requires much more resources in terms of space, time, labour, skills and technology, as well as experience, in order to be performed properly and sustainably. While professional photographers can create and process 2D images of about 30–40 objects in a day, depending on the artefacts, in the same amount of time, they can produce only one to three 3D models. Consequently, before even commencing 3D digitisation, museums should be certain that the effort is actually worth the required investment (Malinen 2019).

If a museum wants to produce 3D models on its own, it needs to invest in adequate digital equipment and software. Like many digital technologies, 3D modelling evolves constantly and will probably become cheaper and more efficient in the future. However, the resource intensiveness of 3D modelling becomes more problematic by the rapid development of digital tools. The high-quality equipment needed for laser scanning is in particular evolving swiftly, which also means that it becomes rather quickly obsolete, and requires new investments in infrastructure. Producing large amounts of 3D models of museum objects may thus be a waste of resources, unless there is a sustainable plan for using the models, or other relevant reasons for modelling.

An alternative to acquiring expensive 3D scanning equipment is to use commercial services. This is a particularly attractive option when 3D modelling is required only temporarily and for a limited number of objects. Outsourcing the scanning activity, however, also has drawbacks, as the museum always loses at least some control over the scanning process and the results. Museum objects might end up handled and transported by persons not trained for the task.

Moreover, inexperienced museums might not take into consideration all the issues related to the standards of scanning and file formats, the metadata accompanying the models and intellectual property rights, which cover both the raw data and the final products (Riksantikvarieämbetet 2019).

When a museum lacks previous experience in 3D modelling, usually it is best to start with small projects. Even when a very limited number of objects are selected for digitising, the museum has to address fundamental questions of both a technical and heritological nature. With small sample sizes, making incorrect decisions is not fatal, and the production processes can be altered with relatively small consequences. Nevertheless, planning remains crucial. The Swedish National Heritage Board has compiled a useful checklist, which museums can follow when planning their 3D modelling activities (Riksantikvarieämbetet 2019):

- What is the overall goal of creating and publishing 3D models (e.g., conservation, documentation, increased availability, replacing or supplementing physical objects, printing copies, digital exhibition, teaching aids, etc.)?
- Does the museum have a vision with which the production and publication of 3D models can be linked?
- What kind of resources, staff, expertise, technical equipment and funding does the museum have for creating 3D models?
- What are the main target groups and what needs do they have?
- Does the museum already have a publication policy, including, e.g., free use, and for whom and why are the 3D models published?
- What channels will the museum be using in publishing the 3D models?
- Does the museum have a plan and facilities for long-term maintenance and updating of 3D data?

The museum should be able to answer this series of questions, at least provisionally, when commencing its endeavour to produce 3D models. In 2020, the European Commission published a document titled *Basic principles and tips for 3D digitisation of tangible cultural heritage*, which was compiled with the help of experts on 3D modelling. It contains ten principles, along with further instructions, to help heritage institutions, museums, authorities and professionals in increasing their use of 3D digitisation (European Commission 2020). The document contains many aspects similar to the Swedish National Heritage Board's list, and should be consulted when planning any form of 3D digitisation of heritage objects.

Since digitising is such a strain on resources, the museum should be able to articulate what added value 3D modelling would actually bring to different end-users instead of, e.g., publishing digital photographs of the same objects online. A justifiable reason might be that through 3D models audiences can visually access museum objects from different angles and observe details which

would not be possible in photographs or by looking at the actual object through a protective glass in an exhibition.

Selecting Objects for 3D Modelling

Much of the published work on 3D modelling of heritage focuses on describing and developing a technological framework. Nonetheless, from the point of view of heritage work, the most important issues relate to selecting the museum objects for digitising and the use of the models in heritage institutions. In fact, the selection of objects and sites for 3D modelling should be the cornerstone of any heritage digitising process, and it is largely determined by the intended audience and the types of 3D models that are relevant to it.

To some extent, the selection of objects for 3D modelling is conditioned by the technological framework, as different digitising techniques pose different kinds of limitations. For almost all the available techniques, there are some materials and shapes that are extremely difficult or almost impossible to model. Data capture has difficulties with such reflective surfaces as lustrous metals, glass and marble, with their translucent and heterogenous structures (Frischer 2016), and, conversely, with very dark surfaces. Thin or otherwise small objects, as well as artefacts with complex and movable parts, can also be problematic. There are some procedures to circumvent such situations. For example, the surface of a shiny object can be sprayed with pigment to create a matte coat for better scanning results, but such techniques might not be suitable for museum objects.

As is typical of the introduction of new technologies to museums, the objects chosen for digitising are often well-known token items, which institutions like to use for their publicity. Sometimes a selection based purely on the popularity of certain museum objects is justified by the reduced handling of such objects. However, as Jacob L. Dahl (2018) points out, the continual development of new and more precise documentation technologies, as well as the unavoidable physical change of all museum objects, means that the same objects are actually documented and digitised again and again, and consequently their handling is not necessarily reduced. Yet, 3D modelling can be pivotal in minimising the need to move and touch very fragile objects after they have been digitised. The frailty of objects and sites as a selection criterion can coincide with the difficult accessibility of the artefacts and locations for visitors. For instance, wrecks and other underwater sites remain unattainable for most.

Besides the criteria of popularity, fragility and accessibility, scholarly research can also be a principle in selecting objects for 3D modelling. Digitisation can bring otherwise inaccessible objects within reach of a larger community of scholars, or enable them to examine objects hosted in different museums at the same time. By the same token, fragments of the same object dispersed in different collections can be reunited, and partly destroyed objects reconstructed by digitally combining documentation from different periods (Dey 2018, pp. 28–30). In some cases, 3D models can also be used for measuring objects precisely.

Increasingly, however, the most exciting applications of 3D models in scholarly research use digital means such as reflectance transformation imaging (RTI) to virtually enhance, manipulate and analyse objects and their properties (Jones et al. 2015; Tolksdorf, Elburg & Reuter 2017).

The selection of objects for 3D modelling in heritage institutions has largely been based on criteria defined and measured by heritage professionals, even when public engagement is the foremost motivation (Jones & Rapley 2018, p. 82). This seems problematic, since the empowerment of communities as part of heritage endeavours and management has a growing impact on the role of museums and how they see their mission. However, many museums are still testing and learning 3D modelling, and probably with more experience the selection process will become more inclusive (Jeffrey et al. 2020). Freya Roe (2014, p. 42) suggests that opening up the selection processes and engaging communities in every step could turn one-off visitors into long-term users. In the future, local communities will perhaps also have better access to 3D modelling infrastructure (Lowe 2018, p. 56), and be able to utilise their own devices, such as smartphones, to digitise heritage objects and sites in crowdsourcing campaigns.

3D Modelling Techniques

The creation of 3D models can be accomplished using various techniques, but in heritage work, there are three main techniques: photogrammetry, laser scanning and structured light scanning. They all have different benefits and shortcomings, and the quality of the 3D models depends on the technical equipment and software, as well as the operator's skills and experience. The best technical result is reached when the geometry of the models, their textures and optical material properties are as high quality as possible. Going for the highest resolution might sound tempting, but as Diane Zorich (2018, p. 75) points out, this creates huge processing and storage demands, which can be impossible to meet. Hence the resolution should be decided based on the actual use of the model. For instance, will the 3D model be part of the scholarly documentation of the object, where the resolution should be high, or is it to be used for public engagement in which lower resolutions are better suited for the task?

The first one of the three techniques, 3D photogrammetry, is a relatively old technique based on converting two-dimensional data obtained from digital photographs into three-dimensional measurements and the final product. In this method, known as structure from motion (SfM), tens or hundreds of overlapping photographs of the object are taken from different angles, and then matched and compiled into a digital model. The photographs can be shot with ordinary digital cameras, but special software is needed to process the image data and generate a dense point cloud, which is a set of spatial coordinates sampled from the external surfaces of the physical object.

Figure 1. Creating a 3D model of a piece of prehistoric pottery with photogrammetry. The item to be digitised is placed on a rotating platform, while the camera takes digital photos of the piece from different angles. Photo: Annukka Debenjak-Ijäs.

Photogrammetry has quickly become easier, faster and cheaper than other forms of digital imaging, especially as the different software tools needed for creating the final products have evolved. Presently, it is the best and least expensive way to start creating 3D models, although it still requires a trained person, preferably a professional photographer with an interest in IT. It is recommended to use advanced shareware or commercial products, of which there are usually trial versions available for free (Agisoft 2019; CaptureReality 2019; Historic England 2017).

Nowadays it is no longer that difficult to do basic 3D photogrammetry using ordinary smartphones with a modelling application. Most of these apps are based on photogrammetry, and many of them are free. The quality of the models and the ease of using the apps vary, but smartphones nevertheless offer a useful way to learn some basic 3D scanning and can create models for temporary use (Obudho 2019). They can also be easily used in crowdsourcing campaigns.

A step up from smartphones is using a digital camera with appropriate lenses and lightning (Etienne 2018; Historic England 2017). When artefacts are being photographed, a tripod and an external lightning rig are a must, and for smaller objects a light tent can be especially handy. In addition, a turntable lessens the need to move either the object or the camera when the required number of images is taken. For terrestrial photogrammetric imaging, a fixed or extendable tripod or mast is needed, while aerial photogrammetry requires a camera drone or other remotely controlled aircraft.

The second technique, laser scanning, also shows great variation in its operating principles, precision, accuracy and price (Artec3D 2019). This technology is based on active data collection, where a laser beam is emitted and received to determine the distance to a surface. In addition to a stationary tripod, the collection of data can be carried out from a vehicle or from the air; even handheld and backpack systems are available, allowing data collection while walking around a site or an object. Many museums have acquired handheld laser scanners, as

prices have become more affordable and their use is quite easy to learn, though some of the devices may not be of the highest quality or have other limitations.

Like photogrammetry, laser scanning has many applications. It is routinely used in archaeological and architectural documentation (Debenjak 2015; Savolainen 2019), as well as in creating 3D models or 2D illustrations of portable artefacts and collecting data for 3D printing. The technique nonetheless has its limitations, and the desired outcome usually requires expensive equipment to attain the highest quality, as well as a significant amount of time for scanning and processing the data.

Most importantly, unlike photogrammetry, laser scanning cannot record the colour data or texture of the surface, which must be added by other means. One solution is to integrate laser scanning data with point clouds created by means of 3D photogrammetry. This kind of hybrid approach to producing high-quality 3D models gives the best results in terms of resolution and texture, especially if the sites and objects are difficult to digitise with a 3D laser scanner alone (Historic England 2017).

Like laser scanning, the third technique, structured light scanning, requires specialised equipment (Dey 2018, p. 24; Historic England 2018). Such a device projects a structured light pattern of stripes and grids onto a surface that is then recorded by an infrared camera. By measuring how the pattern is transformed by the surface, the device calculates variations in depth. The measuring device is often accompanied by a digital camera, which records the colour data of the scanned surface. Structured light scanning is a safe and quick method, as models are often generated in real time on a computer screen. The disadvantages include the need of a controlled environment, as ambient light can affect the quality of the scan, and it produces a low quality of resolution and surface detail compared with the other two methods.

Regardless of the chosen method, a high-performance computer, such as a state-of-the-art gaming computer, is needed to run the software and process the raw data. Usually, the computer should have as much memory (RAM) as possible and run a high-speed multi core CPU for processing the data. Specifically, a dedicated 3D graphics card or graphic processing unit (GPU) is essential. Lastly, ample amounts of data storage space are needed to assist the processing and storing of large data sets (Agisoft 2019; CaptureReality 2019; Historic England 2018).

In addition to the basic recording hardware and software, many manufacturers offer equipment needed for automating the whole process of 3D digitisation (Cultlab3D 2019; Santos 2017). Automated or semi-automated processes may integrate several components. For example, CultArc3D comes with an automated conveyor belt system, glass carrier disks and a scanning station, while other products utilise robotic arms. Some of these solutions were originally designed for the needs of e-commerce and were offered to museums only later, while others were designed and tested from the start to suit the requirements of heritage institutions.

Archiving and Distributing 3D Models and Data

After the 3D model has been processed and finalised, another set of issues emerges regarding the distribution, use and archiving of the results. In fact, for heritage institutions, these are crucial concerns that should be resolved before digitising begins. Firstly, it should be decided how much of the raw material and related datasets are to be preserved alongside the actual model. The final 3D model comprises only a small part of the data collected during the digitising process, and ideally a portion of the other material is also stored. The raw data includes a series of digital images or other digital information. Since digitising technology evolves rapidly, some of this raw data should be preserved for reuse in the future, when the same datasets can be utilised to make 3D models of much better quality and accuracy. Moreover, the preservation of the datasets allows examining the process later and increases its transparency and openness. However, the more datasets kept in digital archives, the larger the storage capacity has to be.

Secondly, transparency and usability of 3D models in heritage institutions requires that they are accompanied by adequate metadata. The term metadata refers to data that is affixed to the actual content to provide information about the model, including the technical framework of the production process, but also the heritage context and content of the model. Each different digital genre usually has specific standards, which define the information that should be provided along with the data, but because 3D modelling is a relatively recent development in heritage institutions, there is no widely acknowledged framework for its metadata. Some museums and organisations, however, have already developed metadata models and offer them for open use (DPO 2018; Europeana Network Association Members Council 2020).

Thirdly, while some of the 3D models are intended for use only in museums, more and more of them are put online for public viewing and use, often under a Creative Commons licence. There are several websites offering free services for publishing, sharing and viewing 3D models. Among the most popular are Sketchfab and Thingverse. In addition, such public platforms for digital cultural heritage as the European Union's Europeana and Finna in Finland are being developed to provide content management and sharing for 3D models as well.

Fourthly, archiving and distributing 3D data requires plenty of storage space and dealing with various interfaces and items of software. It is problematic, however, that supercomputers and cloud-based data storage consume a lot of energy, which goes against the principle of sustainable development. Consequently, when 3D digitisation is planned, sustainability and reducing CO_2 emissions should be taken into consideration. A good starting point for this is the document *Sustainable Development Goals* (SDG) published by the United Nations for 2015–2030 (United Nations 2015).

Uses of 3D Models in Heritage Institutions

Since digitising collections has become popular in heritage institutions, numerous 3D modelling projects are in progress in various parts of the world. Here we present three different Nordic projects, each with its distinct characteristics. The first one is an example of how an archaeological find can be digitised for conservation and public engagement purposes, the second is a project that aims at establishing best practices for 3D modelling and the third shows the successful digitisation of entire museum interiors.

Firstly, in 2019, the Finnish Heritage Agency launched a project to pilot and develop 3D processes in digitising its collections. Even though this was not the first time the Finnish Heritage Agency used 3D methods and created 3D models, the project revealed that embedding 3D modelling into collection management is time-consuming and still requires a lot of experimentation and mistakes to ultimately be successful.

Unlike in many other 3D modelling projects, the artefacts chosen for digitisation varied substantially in size, age, material and significance. A representative example of the chosen artefacts was a portion from a 1684 shipwreck, known as the *Hahtiperä wreck*, found on dry land in the centre of Oulu, Northern Finland in 2019. The find was 3D modelled with photogrammetry before its conservation started, which involved disassembling the remains (Museovirasto 2019). The 3D model could be used to visualise the construction of the ship, but most importantly to reassemble the wreck after the conservation. This and similar 3D projects in Finland and internationally have produced experiences and data which are being developed into best practice guidelines.

The second project is based at the Department of Archaeology at the University of Turku, and was one of the recipients of the Ministry of Education and Culture's special subsidies for the 3D digitising of museum collections in 2018. In collaboration with the Aboa Vetus Ars Nova Museum in Turku and the Turku Museum Centre, the project aimed at digitising archaeological finds from the collections of the three institutions (Immonen & Ratilainen 2019; Turku Museum Centre 2020). In addition to testing and comparing a range of 3D modelling techniques, equipment and practices, the project has also designed and held a university course on 3D modelling with lectures and workshops, and eventually it collected and put all of the latest know-how into an open access guide on best practices in the 3D modelling of archaeological finds (Debenjak-Ijäs 2020). It is common for commentators on heritage 3D modelling to state that the aims and audiences of digitisation should be defined clearly before starting the actual activity, but one of the observations of the Turku project was that many ideas for inventive ways of using 3D models emerge only during and after the actual digitisation. Perhaps 3D modelling projects should have some space for experimentation and making adjustments throughout the process, in order to better reach novel and original outcomes.

Figure 2. A 3D model made of a piece of prehistoric pottery. The item is part of the collection of the Department of Archaeology at the University of Turku. Photo: Annukka Debenjak-Ijäs.

Thirdly, creating 3D models of heritage can bring advantages to both museums and wider audiences, some of which the heritage institutions might not have even imagined. Since 3D models have the potential to allow better access to heritage, regardless of one's location and background, they can reach out to entirely new audiences. A case in point is the Hallwyl Museum in the historical Hallwyl House in central Stockholm. The house, built from 1893 to 1898, belonged to the Count and Countess von Hallwyl, but was donated to the Swedish state in 1920 and opened as a museum in 1938. The house's sumptuous interiors exhibit an extensive art collection. Recently, the museum produced various high-quality 3D models of the museum's interiors and published them online under Creative Commons licences, allowing free re-use also for commercial purposes. The virtual 3D exhibition includes not only the documentation of the museum space and its artworks, but also textual information on individual exhibited items and internet links to other websites.

With the help of 3D modelling, the Hallwyl Museum became available to everyone with internet access, which raised general awareness of the museum, but which did not reduce the number of physical visitors. In 2018 the Hallwyl Museum had a total of 309,434 visits to the physical museum, while the 3D models of museum interiors on Sketchfab alone were accessed over 117,000 times (Hallwyl Museum 2020; Lernestal 2020). As a further benefit, the Hallwyl Museum's 3D models on Sketchfab were utilised in many virtual reality and other projects. Through these secondary applications users and players in virtual reality around the world came into contact with cultural heritage of the Hallwyl Museum (Lernestal 2020).

3D Models as a Heritage Phenomenon

The introduction of 3D models in museums involves many technical and practical problems, as well as imposing infrastructural demands. Importantly, the digitisation of heritage objects and sites also brings up issues of a more conceptual and cultural nature. These require further research and analysis, and remain to be fully addressed by future scholarship. However, in this concluding section of our article, we have identified three areas of particular interest which should be taken into consideration when museums engage in 3D modelling of their col-

lections. The first is the relationship between museum objects and their digital surrogates, the second is the user experience and engagement with 3D models and the third is the role of museums as digitising institutions.

From a technical point of view, the relationship between museum objects and their digital surrogates is largely defined by the 3D model's accuracy and precision in representing its physical original. The situation is more complicated, however, if this relationship is seen as also affecting our culturally and socially conditioned relationship with objects. Like the artefacts in museum exhibitions, 3D models are encountered and seen in a historically conditioned framework, mixing our real and virtual encounters with artefacts. In fact, 3D models bring together very different kind of audiences to experience museum objects in digital space, which is very dissimilar to the museum environment. For instance, unlike physical objects, which are affected by continual, although not necessarily rapid change, 3D models are frozen images from the material itinerary of their real counterparts (Jones & Rapley 2018, p. 83). This forms a stark contrast with the way modern conservation and preservation of heritage objects embraces the continual physical change of artefacts and sites.

It is revealing of our historically conditioned relationship with museum artefacts that the objects chosen for digitisation are almost always finished products and usually of high material value, not half-finished products, tools of manufacture or otherwise less valued items. Tiia Suorsa (2017) argues, in contrast, that 3D modelling should take more into consideration the actual production and use processes of which the heritage objects have been part. Digital models should allow heritage items to be seen as unfinished and perpetually changing. Nevertheless, although 3D modelling could open up novel ways of thinking about our relationship with museum artefacts, and some scholars have called for a radical reconsideration of digital heritage, presently the applications of 3D digital technology tend to reiterate ossified conceptions of heritage objects and their valuation.

Among the applications of 3D modelling is a physically accurate reproduction of the original artefacts with 3D printing. This is a process in which some raw material is joined or solidified under computer control to create a physical 3D object. 3D printing makes it possible to manufacture copies of heritage objects for the commercial market, but there are also more inventive applications, like the creation of tactile replicas, which museum visitors can touch and handle. Printing physical copies of objects can even help heritage institutions to address issues of repatriation and the decolonising of collections (Samaroudi & Rodriguez Echavarria 2019). Moreover, instead of exact copies, 3D printing has been used to create physical puzzles or puzzle-like objects to engage audiences in museum exhibitions (Rodriguez Echavarria & Samaroudi 2018; Samaroudi et al. 2017).

Besides the object-focused approach, the second area of interest in 3D modelling involves the users of the digital surrogates. It is slightly misleading, however, to integrate the terms user and user experience from a commercial context into the analysis of 3D models in a heritage environment. The terms problematically cast

the variety of encounters with 3D models into an abstracted notion of a uniform user and his or her stereotypical experiences. Whatever terms are chosen, there are pivotal questions of 3D modelling to be studied in museums (Li et al. 2018). On the one hand, the questions are relatively uncomplicated, addressing, e.g., the user profile. Is the intended audience of the 3D model already experienced with heritage institutions, i.e., regular museum visitors, or are they members of the public who rarely go to museums? On the other hand, 3D modelling raises rather intricate questions regarding the technology's cultural implications. How do 3D models change our understanding of the past and ancient artefacts, as well as our experiences of heritage? Museums have traditionally controlled visitors' behaviour in a highly assertive manner, thus creating homogenous embodied experiences of heritage spaces. However, digitisation, including 3D modelling, potentially challenges the idea of a passive, obedient body in the museum environment, offering fresh means for "mapping and remediating the tangible and intangible heritage encompassing embodiment" (Kenderdine 2016, p. 23). How do these digitally created virtual environments alter the embodied interpretation of heritage? The effects of heritage digitisation are manifold, covering various factual, emotional, institutional and individual spheres of life. Despite the importance of questions concerning the impact of digitalisation on heritage, research on the variety of encounters between 3D models and people is still more limited than studies on the technological aspects of 3D modelling.

Thirdly, 3D modelling, along with other forms of digital technology, necessarily alters museums and other heritage institutions. Digitising creates new demands for the museum infrastructure in terms of both equipment and online presence, as well as for personnel with practical knowledge of how to use the new technologies (Roe 2014). Some of these technical challenges can be mitigated by establishing new forms of collaboration among individual museums, as well as among museums and other actors in the heritage sector. Museums could, for instance, share their equipment and experiences of 3D modelling among themselves. There are, however, even broader institutional challenges. For instance, as Suorsa (2018) points out, digital heritage calls into question the established distinction between heritage institutions and audiences, epitomised by the glass case which separates the heritage object and its viewer. In contrast, 3D models are potentially available to everybody and allow equal access to heritage, whether you are a professional, amateur or even just passingly interested in some item of heritage.

As digital and cultural phenomena, 3D models are highly flexible and multifaceted objects (Fay-Leino 2016, p. 15), and unleashing their potential requires not only technological know-how, but also a historically sensitive approach. If these two aspects of 3D modelling are successfully combined, it will potentially break new ground in heritage institutions. At their best, 3D models could help turn single-visit museumgoers into persons with an enduring interest in heritage and culture.

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