Marco Hostettler · Anja Buhlke ·
Clara Drummer · Lea Emmenegger ·
Johannes Reich · Corinne Stäheli *Editors*

The 3 Dimensions of Digitalised Archaeology

State-of-the-Art, Data Management and Current Challenges in Archaeological 3D-Documentation

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Marco Hostettler studied Prehistoric and Medieval Archaeology at the Universities of Bern, Berlin and Zurich. Currently he is employed in the Department of Prehistoric Archaeology at the University of Bern. In his ingoing PhD thesis he is specialising in the investigation of prehistoric land-use in the Bronze Age Southern Balkans. His research interests cover the Neolithic and Bronze Age in Europe as well as digital methods in archaeology.

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Part I
History and Perspectives of 3D Application in Archaeology

Chapter 1
3D Archaeology and Cultural Heritage: Where Are We Today?

Marco Hostettler, Anja Buhlke, Clara Drummer, Lea Emmenegger, Johannes Reich, and Corinne Stäheli

Abstract Although the basics of 3D technologies developed rather early on, only today are we seeing a steep increase in the application of 3D technologies in archaeological practice. This volume aims to give a broad overview of possible applications in the field, but also to open a discussion about the challenges and problematic aspects of this method so far. Only if there is an awareness of the implications and challenges of implementing this new technology in the everyday practice of field and research archaeology can archaeology take full advantage of its possibilities.

Keywords 3D technologies in archaeology · Digital archaeology · Digital archiving · Data management · Photogrammetry · 3D scanning in archaeology

The application of new methods has had a lasting impact on our research questions, research setups and applied methodology – in short, they have deeply affected our understanding and practice of archaeology. Some of them have been labelled

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revolutionary, such as radiocarbon dating and dendrochronology or ancient DNA analysis (cf. Kristiansen 2014). The 3D capture of archaeological findings and artefacts may also be one such method, with the potential to revolutionise archaeological documentation.

An important foundation for 3D capture is the method of photogrammetry, which has a very long history dating back to the very beginnings of photography in the nineteenth century (Luhmann et al. 2014). The basic mathematical principles establishing the numerical relationship between the real-world object and its photographic representation were already developed and understood at that time. One important field of application was the metric recording of façades, a technique used by the German Albrecht Meydenbauer to record a range of important architectural monuments in the German Reich and neighbouring countries. In addition to monuments such as the cathedral in Worms or the Haut-Koenigsbourg in Alsace, he recorded the ruins of Baalbek from 1902 until 1904. His efforts count among the earliest attempts at the preservation and documentation of cultural heritage via photogrammetry (Luhmann et al. 2014; Grimm 2021).

During the first half of the twentieth century, analogue photogrammetric methods using fixed and rigid camera systems in combination with visual plotting systems were prevalent. The main application was mapping, mostly using aerial photography. Close-range photogrammetry was only rarely used, for instance in police work with specially developed systems. Subsequently, from the 1950s onwards, numerical methods were increasingly developed. Together with recent developments in computer vision, these methods enable a more flexible and accurate model reconstruction, including from arbitrary images and camera locations. From the 2010s onwards, a wide range of easy-to-use software packages came on the market, which enable quick and cost-effective close-range photogrammetry (Luhmann et al. 2014).

These tools made it possible to capture objects, such as archaeological artefacts, excavations, and even entire landscapes, in three dimensions with an accurate reconstruction of sizes and ratios, as well as accurate surface and texture representation. These methods not only enable the eye-catching display of digital models, but also enhance research possibilities (e.g. for their application in labour-cost studies, see Pakkanen et al. 2020; for a recent comparison of different methods for site recording, see Stamnas et al. 2021). Measurements can be taken more accurately during post-processing, while different mapping techniques can be applied to the data. They also make possible the integration of different datasets in a 3D space (e.g. in an integrated approach using GIS in Katsianis et al. 2008, to calculate the tonnage of a marble cargo in Roman ships in Parizzi and Beltrame 2020 and to map masons marks in Orabi 2020). In this way, these tools not only represent a new and more accurate approach to documentation, but also open a new dimension in which research questions can emerge (see Brysbaert et al. 2018, with examples of the application of 3D technology to the specific question of labour cost).

Nevertheless, until the middle of the last decade, the scientific value of the application of virtual archaeology (VA) and 3D archaeology was still being discussed, if not questioned, while the methods themselves seemed to remain constantly in a pioneering state, as suggested by the fact that this method was perceived as revolutionary even into the mid-2010s (Lanjouw 2016; Vergnieux and Giligny 2016; De Reu et al. 2014). This situation is even more surprising if we consider that the first attempts to introduce all the relevant methods, such as CAD, virtual or photogrammetric 3D reconstruction, into archaeology had been made already in the 1970s, 80s and 90s (for an overview, see Lanjouw 2016).

One possible reason that these methods have only recently become widespread could be the increased acceptance and easy accessibility of computers and other digital tools. Not only have the costs of computer hardware and digital cameras decreased in the last decade (e.g. U.S. Bureau of Labor Statistics 2015), but software used in reconstruction, post-processing and analyses has become more user-friendly and efficient. Another possible reason is the increasing interconnection of the world, which has helped further promote these technologies since the advent of the internet in the 1990s. In this respect, the predictions and visions of various archaeologists formulated as early as the 1970s have only recently been fully realised (compare the following summaries of early views on digital archaeology: Frischer 2008; Lanjouw 2016; Hodel 2020). In 2008, Bernard Frischer and Anastasia Dakouri-Hild (Frischer and Dakouri-Hild 2008) collected a wide range of papers in *Going Beyond Illustration* and presented diverse methods for virtual and 3D archaeology that were thought to permit the scientific exploitation of these tools, which had previously been perceived as mainly fulfilling educational and visualisation purposes (Frischer 2008). In an anthology published in 2016 by Hans Kamermans et al. entitled *The Three Dimensions of Archaeology*, different papers presented various approaches to the scientific and research-oriented application of three-dimensional methods, while in 2018 Barry Molloy edited a topical issue in the journal *Open Archaeology*, with a focus on advances in the use of 3D models in archaeology.

In 2014, the need for best practices was addressed by an anthology aspiring to serve as a guideline in the 3D documentation of Cultural Heritage (Remondino and Campana 2014). The book covered a range of topics starting at the intersection of archaeology and geomatics, including papers on laser/lidar, photogrammetry, remote sensing, GIS and virtual reality. Three case studies containing practical insights were included at the end, while the body of the book focused on establishing the basic principles governing the application of these techniques to archaeology and cultural heritage. Other publications also pointed in the same direction, covering the methodological basics and providing first-hand case studies of the application of 3D techniques at excavations (cf. De Reu et al. 2014; Galeazzi 2016; Novaković et al. 2018).

Nonetheless, the widespread introduction of digital-capturing techniques poses new challenges: the acquisition and processing of 3D data produces a vast amount of data that needs to be archived (cf. Chen 2001; Zubrow 2006; De Reu et al. 2014). Since archaeologists must document each step, this also includes the documentation of processing steps and the modelling of 3D data. The interoperability and exchange of 3D models – not only between individuals, but also between programs – is not yet fully developed. Going through the 'chaîne opératoire' of 3D data, we encounter another challenge, namely that the visualisation and publication of 3D models for everyone also has its pitfalls, including data formats, the need for special software, limitations on web access and the question of copyrights. Who owns a 3D model?

The museum that possesses the find, the photographer or the individual who processed the data?

Still, for many archaeologists, not only the production, but also the handling of 3D technologies is new. Where are we now? And where do we want to take 3D technologies in archaeology and cultural heritage? This book provides an overview of the current applications and pitfalls of image-based 3D technologies in archaeology and cultural heritage. It also addresses existing practices and the use of 3D data for documentation, research and visualisation. It should not be seen as a comprehensive handbook, but rather as capturing the current state of 3D technologies in archaeology. As such, it is organised into five parts covering important aspects of 3D archaeology, such as its history and the context of its application, case studies showcasing different applications with a strong research focus, the presentation and organisation of 3D data, archiving and data management.

In Part I, following this short introduction, Jugoslav Pendić and Barry Molloy (Chap. 2) offer a comprehensive account of the application of 3D technologies in archaeology, while also highlighting some of the weaknesses seen so far and pointing out a way forward for future use. In contrast, the contribution by Florian Innerhofer, Thomas Reuter and Conny Coburger provides insights into the use and development of 3D technologies over the last 15 years in day-to-day archaeological practice at the Archaeological Heritage State Office of Saxony (Chap. 3).

Part II focuses on the gathering of 3D data via different case studies, attempting to give an overview of 3D technologies: i.e. what their current use is and what kind of data and methods are applied in different archaeological contexts. It covers a range of topics, from the documentation of larger archaeological sites, including standing remains, as in the paper by Clemens Brünenberg, Christoph Rummel and Monika Trümper (Chap. 4) on the Pompeian baths, to spatial analysis of the fragmentation processes of pottery using photogrammetry and GIS analysis, as applied by François Fouriaux (Chap. 5).

Going one step further, Part III is designed to present possibilities and workflows to enhance the study of archaeological material through the use of 3D technologies. Christian Horn, Mark Peternell, Johan Ling, Ashley Green and Rich Potter explore the advantages of 3D documentation in research on rock art, while also discussing problematic aspects of this technique (Chap. 6). Elisabeth Trinkl, Stephan Karl, Stefan Lengauer, Reinhold Preiner and Tobias Schreck used 3D technologies for typological studies and to produce an enhanced visual representation of Greek pottery paintings (Chap. 7).

In Part IV, the focus is on how to present and communicate 3D data to different audiences. Tracing the adaption of the potter's wheel technology, Loes Opgenhaffen, Caroline Jeffra and Jill Hilditch make use of 3D technologies and show how they present their insights, including metadata and paradata (Chap. 8). Commenting on the database they develop for the 3D documentation of bones, Jugoslav Pendić, Jelena Jovanović, Jelena Marković and Sofija Stefanović elaborate further on the topic of how to present 3D data and how to transmit insights to other researchers (Chap. 9). Kate Fernie focuses on the web portal EUROPEANA and the experience of making the visualisation of 3D data available on the web to a broad audience (Chap. 10).

Part V deals with the challenges relating to archiving all the data related to the use of 3D technologies for archaeology and cultural-heritage management. The survey of the current application of 3D technologies in archaeology by Marco Hostettler, Anja Buhlke, Clara Drummer, Lea Emmenegger, Johannes Reich and Corinne Stäheli gives a comprehensive overview of different groups and their needs when it comes to handling 3D data (Chap. 11). Kristin Kruse and Esther Schönenberger share their experiences from the archaeological department of the canton of Zurich, explaining how to document and generate 3D models, but also how to create a sustainable archive and data management system (Chap. 12).

This broad selection of topics ranging from data collection to analysis and presentation is intended to enhance our understanding of the current position of 3D technologies in archaeology. It demonstrates existing practices and workflows that are applied today, but also gives clues about possible pitfalls and how experienced users find ways to work around and potentially resolve them. Furthermore, it reveals not only flaws in the workflow of 3D documentation, but also the need to arrive at a fundamental agreement in archaeology and cultural heritage about the implementation and standardisation of the application across different groups of interest, one that not only covers current needs but also has a future generation of users in mind. The book closes by contextualising 3D archaeology as part of a larger digital world. Besides technical challenges the ethics of the digital and an awareness of the underlying power structures are key for a sustainable and revolutionising future (Chap. 13).

References

Brysbaert A, Klinkenberg V, Gutiérrez Garcia-Moreno A, Vikatou I (eds) (2018) Constructing monuments, perceiving monumentality & the economics of building: theoretical and methodological approaches to the built environment. Sidestone Press, Leiden

Chen S-S (2001) The paradox of digital preservation. Computer 34:24–28. https://doi.org/10.1109/2.910890

De Reu J, De Smedt P, Herremans D et al (2014) On introducing an image-based 3D reconstruction method in archaeological excavation practice. J Archaeol Sci 41:251–262. https://doi.org/10.1016/j.jas.2013.08.020

Frischer B (2008) Introduction. From illustration to digital heuristics. In: Frischer B, Dakouri-Hild A (eds) Beyond illustration: 2D and 3D digital technologies as tools for discovery in archaeology, BAR international series 1805. Hadrian Books, Oxford, pp V–XXIV

Frischer B, Dakouri-Hild A (eds) (2008) Beyond illustration: 2D and 3D digital technologies as tools for discovery in archaeology, BAR international series 1805. Hadrian Books, Oxford

Galeazzi F (2016) Towards the definition of best 3D practices in archaeology: assessing 3D documentation techniques for intra-site data recording. J Cult Herit 17:159–169. https://doi.org/10.1016/j.culher.2015.07.005

Grimm A (2021) Albrecht Meydenbauer: Bauingenieur – Fotograf – Photogrammeter. PFG 89:371–389. https://doi.org/10.1007/s41064-021-00183-8

Hodel T (2020) Perspektivenwechsel: Zwei Disziplinen aus Sicht der Digital Humanities – oder wie sich die Geisteswissenschaften im Digitalen (selbst) finden. Zeitschrift für Schweizerische Archaeologie und Kunstgeschichte ZAK 77:101–110. https://doi.org/10.7892/BORIS.147227

Katsianis M, Tsipidis S, Kotsakis K, Kousoulakou A (2008) A 3D digital workflow for archaeological intra-site research using GIS. J Archaeol Sci 35:655–667. https://doi.org/10.1016/j.jas.2007.06.002

Kristiansen K (2014) Towards a new paradigm? The third science revolution and its possible consequences in archaeology. Curr Swed Archaeol 22:11–71

Lanjouw T (2016) Discussing the obvious or defending the contested: why are we still discussing the 'scientific value? Of 3D applications in archaeology? In: Kamermans H, Neef W, Piccoli C, Poluschny AG, Scopingo R (eds) The three dimensions of archaeology: proceedings of the XVII UISPP world congress (1–7 September 2014, Burgos, Spain), vol 7. Archaeopress, Oxford, pp 1–11

Luhmann T, Robson S, Kyle S, Boehm J (2014) Close-range photogrammetry and 3D imaging. Walter de Gruyter GmbH & Co KG, Berlin/Boston

Novaković P, Horňák M, Zachar J (eds) (2018) 3d digital recording of archaeological, architectural and artistic heritage. Znanstvena založba Filozofske fakultete Univerze v Ljubljani. Ljubljana University Press, Faculty of Arts

Orabi R (2020) Masons' marks in Aleppo, a study of a defensive tower in old Aleppo: using 3D laser scanning and photogrammetry for identification and classification. Digit Appl Archaeol Cultural Herit 19:e00154. https://doi.org/10.1016/j.daach.2020.e00154

Pakkanen J, Brysbaert A, Turner D, Boswinkel Y (2020) Efficient three-dimensional field documentation methods for labour cost studies: case studies from archaeological and heritage contexts. Digit Appl Archaeol Cultural Herit 17:e00141. https://doi.org/10.1016/j.daach.2020.e00141

Parizzi S, Beltrame C (2020) Calculating the tonnage and the dimension of the cargoes of marble of Roman period. Digit Appl Archaeol Cultural Herit 18:e00153. https://doi.org/10.1016/j.daach.2020.e00153

Remondino F, Campana S (eds) (2014) 3D recording and modelling in archaeology and cultural heritage: theory and best practices. Archaeopress, Oxford

Stamnas A, Kaimaris D, Georgiadis C, Patias P (2021) Comparing 3D digital technologies for archaeological fieldwork documentation. The case of Thessaloniki Toumba excavation, Greece. Int Arch Photogramm Remote Sens Spatial Inf Sci XLVI-M-1–2021:713–720. https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-713-2021

U.S. Bureau of Labor Statistics (2015) Long-term price trends for computers, TVs, and related items. TED: The Economics Daily. https://www.bls.gov/opub/ted/2015/long-term-price-trends-for-computers-tvs-and-related-items.htm. Last accessed 22 Nov 2022

Vergnieux R, Giligny F (2016) Pour un usage raisonné de la 3D enarchéologie. Les nouvelles de l'archéologie. Open Edition Journals 146. https://doi.org/10.4000/nda.3818

Zubrow EBW (2006) Digital archaeology. A historical context. In: Evans TL, Daly PT (eds) Digital archaeology: bridging method and theory. Routledge, London/New York

Chapter 2
The Use of 3D Documentation for Investigating Archaeological Artefacts

Jugoslav Pendić and Barry Molloy

Abstract While 3D rendering of archaeological features in the field is becoming a standard documentary procedure, in the case of objects it remains less well-integrated as a functional resource, when compared to conventional illustration and photography. This paper examines the current state of the art for 3D data workflows, as used in the study of material culture in archaeology. In doing so, we touch upon the historical-technological background of this mode of documentation and observe its current level of impact on what we may consider normal ways of interacting with archaeological assemblages. We underline how current data-management and production issues diminish potential interoperability across 3D model-making platforms and lead to an escalation in data-storage consumption.

Keywords 3D heritage · Digitalization · Knowledge dissemination · 3D production

2.1 Introduction

Since 2010, there has been an increasing shift from debating the value and modes of application of 3D models in the formal documentation of features of archaeological sites (Callieri et al. 2011; Koutsoudis et al. 2013) to their use as a common toolkit, integrated with other spatial technologies (Huang et al. 2016; Pepe et al. 2021). The initial excitement and novelty have given way to routine acceptance and utilisation.

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In particular, the emergence of technical methods that can use simple consumer-grade cameras and inexpensive software on home computers (and even laptops) has enabled what may be considered a revolution in on-site recording. Especially in complex, stratified or urban settings, the limitations of 2D, which requires multiple phase plans, and the difficulties of plotting features that are vertically separated from a few centimetres to several metres have been addressed by a 3D product that simultaneously documents each stratigraphic layer to within almost a centimetre (Martínez-Fernández et al. 2020). These models can be rotated or truncated, and drawings and sections can be extracted. Even when an excavation takes place in phases or over seasons, previously unarticulated parts of the excavation layers can be digitally joined together and restored in a 3D environment. In this sense, this new tool for recording spatiality in a predominantly visual way filled an existing niche within the discipline, and so was adopted with relative ease. A brave new world seemed to open up, accessible even to a novice, with familiar tools that were already present in research facilities (in our experience (JP), a camera and a scale were enough to start in 2013, with the integration of total stations and GPS rovers following soon thereafter). Indeed, in the excavations at the site of Keros in the Cyclades in Greece, a fully digital recording system was in place, which rapidly integrated 3D models into a seamless document-interpreting system (Boyd et al. 2021).

However, while the method used to generate the data was relatively novel (Koutsoudis et al. 2013), the underlying utility of the data thus produced was not. By that point, the distinctive features of 3D-model generation technology had already been present in cultural-heritage management for years. Looking back, a contemporary practitioner would find familiar sights produced by portable scanners and image-based reconstruction software, as well as various uses of non-metrical data from digital cameras for 3D digitalisation work (Beraldin et al. 1999; Pieraccini et al. 2001; Bohler et al. 2001; Maestri et al. 2001; Koisitinen et al. 2001). Moreover, not just the equipment would be familiar: the whole zeitgeist accompanying the vigorous adoption of 3D digitalisation seen at the beginning of the twenty-first century has continued for decades with undiminished passion (see, e.g., the affectionate title composition of Jones and Church 2020, ‘Photogrammetry is for everyone’).

2.2 The Affordability of 3D Scanning

The generation of 3D models from digital photos came to be known colloquially – if not entirely accurately from a technical perspective – as ‘photogrammetry’, and more specifically as ‘image-based modelling’ (Remondino and El-Hakim 2006; Quan 2010). It triggered a new wave of enthusiasm in cultural heritage, introducing a great number of field archaeologists to the possibilities of 3D documentation. Some identify the period of change with the growth of the concept of photo-tourism (Snavely et al. 2006, 2008). Indeed, the volume of photography generated since the introduction of the digital camera has been exponentially greater than that produced in the era of print photography. Gone is the time of a handful of carefully selected photograph opportunities per site, to be replaced by a deluge of frames snapped one after the other in the pursuit of the perfect one. The possibilities this innovation presented for structure-from-motion solutions were clear. Around this period, terms like ‘cost-effective’, ‘affordable’, ‘off-the-shelf’ and so on started to be associated with photogrammetric solutions and lived up to their billing. Digital reconstructions of the archaeological record had become a striking sight, even when made by ‘untrained’ hands using off-the-shelf equipment. The wide range of applications for image-based modelling methods and the rich output it produced, combined with its affordability, led to a steady increase in its use (cf. Remondino 2013; McCarthy 2014; Dubbini et al. 2016; Carvajal-Ramírez et al. 2019; Pakkanen et al. 2020). But even this rapid uptake was more of a change of pace than a radical innovation.

The foundation upon which this quiet revolution was built can be traced further back into the past, all the way to the late 1970s, by way of the 1980s and 1990s (Snavely et al. 2008; Granshaw 2018). Image-based modelling programs marketed today reflect the function that photogrammetry has had for more than a century: resolving 3D positions from disparate camera views (Granshaw 2018). Rather than constituting a fundamental innovation, the rise of image-based methods was largely a matter of fitting the shoe to the foot. This unfolded over many years, although the pace was perhaps determined by technological restrictions and cost more than by the concept itself. Recent changes in hardware availability and affordability, coupled with software becoming better optimized and more user-friendly, have also been a critical development (Hostettler et al., this book, Chap. 11). We can also observe that there was a process of accumulating experience at work. As the technology and techniques became established, a shift occurred from a handful of researchers/vendors/projects with access to the tools and resources to a generation of dedicated users – many of whom could be called ‘digital natives’ – embracing and using the technology. Their combined experience, as well as their dialogues and cooperative endeavours, would eventually come to embody a new, more mature mentality in 3D content production in general and in archaeological fieldwork in particular.

It was not just that the photogrammetry and computers became available to the masses – dedicated systems for 3D scanning had also stimulated non-specialist users to develop creative technical solutions. Budget-friendly scanning set-ups requiring some DIY skills emerged, which used a line laser and camera sensor as the basic tools for 3D digitalisation (Winkelbach et al. 2006, but see also Zagorchev and Goshtasby 2006). This occurred around the same time as the appearance of photo-tourism, and once they were market-ready, these and other 3D scanners were very effective, opening up the possibility of digitalising artefacts in-house (Todorov et al. 2013) and, more importantly, of digitalising them *wholesale* (Revello et al. 2016). Similarly, while the equipment adapted to environmental/terrestrial 3D scanning remained sufficiently expensive that it was restricted to the realm of specialised and comparatively costly projects, mobile and lightweight designs were developed to the point where one operator was sufficient to produce accurate measurements of complex exteriors/interiors. This was a major improvement over the cumbersome techniques that had been used only a few years before (see Koisitinen et al. 2001).

Once again, the game-changer here was that the operator did not need to have a narrow background in surveying or infrastructural design. In our experience (JP), Faro Focus3D from 2015 was an accessible environmental digitalisation tool, requiring no formal training.

From publications to popular platforms like Sketchfab, it is evident that professional archaeologists have become familiar with documenting in 3D, and indeed a great many can be considered proficient practitioners. The availability of high-quality models from both institutional and private model collections demonstrates the presence of a multitude of well-trained and talented model-makers. Clearly, the novelty has come and gone, but an ongoing fascination with digital replicas and a replication remains, in the form of a certain excitement. That said, the potential of the data that has already been generated still has not been exploited. The aforementioned experienced users have both the know-how and the acumen to apply their knowledge effectively, producing 3D content that exhibits nuances that can be considered the product of expert choices rather than automated results. The focus of the discussion is now shifting to new and different agendas. We can make models in site-based archaeology that can be easily circulated and that have archival and analytic potential, but the pressing question is how we can better use them and integrate them into existing, or even new, study routines or workflows, and in particular into artefact study. In seeking to solve the problem of how to effectively manage collected data, we are increasingly asking why we should generate 3D documentation in the first place and, more to the point, how we can more effectively use this to encourage the dissemination of knowledge to a broader audience, including beyond academia. For example, in research funded by the Irish Research Council and published in a dedicated volume of the journal *Open Archaeology*, 3D practitioners explored how models of material culture can create dialogue within and beyond the field, as well as encouraging new ways of thinking about materiality itself within the discipline (Opgenhaffen et al. 2018). The question posed was: how can digital versions of real things encourage novel ways of analysing, understanding and disseminating these objects that go beyond conventional methods?

2.3 The Aggregation of Data

2.3.1 Introduction

This section will identify general steps and key decision-making points in the workflow, in order to reveal the variety inherent in the data structure over the course of the production process. In brief, both core data and the final 3D model can be reinterpreted multiple times, for various purposes, with each stage generating new sets of information to incorporate into the storage scheme and the production pipeline. All reported decision junctions in the process multiply by the number of the objects that are intended to be documented in 3D.

At present, there is a massive user community behind almost every commercial and non-commercial solution for 3D scanning, be it hardware or software. Photogrammetry and affordable 3D scanning has been embraced in many industries. Some of these have common interests with the cultural-heritage community, and archaeology in particular. More importantly, through commercial interactions, some will be better networked with software companies, enabling them to influence the direction of future development and customisation of the market and the appearance of the standards used for the collection of 3D information.

2.3.2 Main Contributors

We use the term ‘dedicated’ to refer to all of the many prefabricated, commercially available 3D surface-scanning solutions, and we use ‘image-based scanning’, ‘image-based method’ or ‘photogrammetry’ for custom-made scanning rigs, which commonly rely on the use of consumer-grade cameras. We are, of course, cognisant that there is some overlap between the first two categories. Finally, we use ‘volumetric scanning’ when speaking of CT and micro-CT scanning. Although we recognise that archaeological 3D content can be created through the usage of instruments and techniques (contact 3D scanning or manual modelling), we have chosen to omit these from consideration here due to their relatively limited presence in comparison to other solutions.

Although dedicated systems are usually made to service particular industry needs, including scanning the built or natural environment, there is frequently an overlap between potential uses. A scanner mainly designed to document objects may also serve, to a limited extent, to scan sections of the environment. Likewise, a scanner for the environment may be used to scan objects, generally larger ones. For present purposes, both will initially generate datasets that require some level of postprocessing and can provide or exert the use of proprietary formats. The number of proprietary formats is likely as large as the number of vendors dealing with scanning equipment. The processing of the data might include conversion into a data structure that is more familiar to the operator, followed by the mechanical trimming of scans (and it may happen that there is not just one scan, but hundreds), statistical trimming of outliers and clutter data. If the target was covered with more than one scan, the scans will need to be co-registered, typically using manually or automatically introduced reference points. The whole collection of scans will probably also need to be georeferenced using a state coordinate system or some other project-prescribed (locally devised) projection. The project parameters might necessitate a workflow that favours working with point or surface data or particular colour information assigned to the data. In order to achieve this, it is commonly necessary to switch between a range of different software options in order to make each necessary modification. This, in turn, can create new types of information which need to be indexed and incorporated into the project scheme.

The image-based methods, recognised for their low barriers to entry, depend on the collected imagery, be it a predesigned acquisition or a haphazardly collected/crowd-sourced one. A key case study for this latter approach in the cultural-heritage sector was the 3D reconstruction of the Temple of Bel and Arch of Triumph (Wahbeh et al. 2016; Wahbeh and Nebiker 2017), as well as other sites (Vincent et al. 2015; Vincent and Coughenor 2016; Stathopoulou et al. 2015) that were destroyed by militant groups or natural conditions. These methods may combine images taken from a variety of devices and formats (phone camera or even video), in various resolutions. Consequently, there may be less control over output quality. The ideal situation is to work with images in RAW format, which allow a high degree of user intervention and have no compression factor.

For example, a complex lighting scenery can be effectively mitigated by flattening illuminated or concealed sections of the scene or object, in order to colour-correct and enhance the image. This is the author's (JP) preferred means of quality control. It requires processing images in RAW format using software capable of converting the processed image into a consumable format, such as a lossless TIFF or a compressed JPEG. In the next stage, a researcher must choose which program to use. What is rarely acknowledged is that while image-based modelling is a passive method of scanning, the software is less passive: it creates its own dependencies during production, cached information to facilitate the reconstruction or to simply speed up different phases of work with the images. These branch out beyond the scope and location of the data being worked on, requiring management to prevent cluttering. Moreover, specific segments of the operation can be saved for posteriority or exchange between different programs. For example, solved camera networks (positions of the camera in space during data acquisition), depth maps and image masks can be transferred from one operation to another, possibly with different spatial extents (data chunking). Similar to the data generated using dedicated systems, object/space geometry can be provided as a point cloud or surface, as a coded raster or as something else entirely, and can undergo further work.

Volumetric imaging methods, such as CT and micro CT, are not specifically tailored to creating surface models, although this is possible. Medical CT scans and micro CT both create a set of 2D images, which represent the basis for generated models and analytic use. Material science-focused micro CT will typically generate scans with a higher spatial resolution than medical CT systems, which are designed for complete/partial body scans. The primary application of CT data has stimulated the utilisation of standardised formats, such as DICOM, to ensure interoperability (Kahn et al. 2007), although other image options may be available. The image sequences produced are corrected for misalignment resulting from the heating-up of the source of irradiation or stage and sample movement, as well as (in multipart scanning) when the object outmatches the field of view. Post correction, grayscale projections are coded to black-and-white bitmap sections which are used to reconstruct a surface model (.ply or more commonly STL). The raw model does not contain any colour information and relies heavily on redaction, especially on contact areas between holder/support platform/wax stabiliser (valid for both micro and medical CT scanners).

2.3.3 Deliverables

We would like to consider a case involving a cultural-heritage office's response to the workflow and documentation processes in the production of image-based models. In 2017, the section for the digitalisation of cultural heritage and modern creativity at the Ministry of Culture and Information of the Republic of Serbia produced 'Guidelines for the Digitalisation of the Cultural Property of the Republic of Serbia' (Ministarstvo kulture i informisanja 2017) which contains a table (Table 2.1) listing the property of the data collected during the process of 'Digitalization of 3D objects by photography'. While the document is not legally binding, as the title indicates, it is intended to provide best-practice guidelines. It does not engage with the management of data generated using a dedicated 3D surface or volumetric system. Rather, its core focus is on image-based scanning, which is no doubt a result of the perception that a lower starting investment is needed for image-based modelling than for more custom-built solutions. As a consequence of the combined ease of access and affordability of image-based methods, this is, in part, also a product of a greater degree of engagement between practitioners who regularly use this approach and museum curators.

While the definitions in this table are incomplete and are premised on a somewhat nonorganic flow of image-based reconstruction, the importance of standardising 3D model acquisition is recognised. Furthermore, two important classifications of digital products are identified – a 'master' and an 'operative' copy – a division that had already been recognised in the context of archaeological fieldwork (Apollonio et al. 2012). The master copy may be loosely defined as containing the highest level of detail that can be achieved with respect to image resolution/GSD,

Table 2.1 Table of data properties and structures, as suggested by the MoC-RS 'Guidelines for the Digitalisation of Cultural Property'

Digitalisation of 3D objects by photography	
Master copy (long-term deposition)	
Record format	RAW HD resolution
Resolution of the record	Maximum supported by the sensor (not less than 6 mp)
Minimal resolution of digital archive	300 dots per inch (dpi)
Format of data archive	RAW and RAW format converted to uncompressed .tif
Colour depth	8 bits per channel Full colour 24 bits
Colour space	RGB
Colour reproduction accuracy	Tonal chart
Operative copy (for exchange, web publishing)	
Resolution	72–150 dots per inch (dpi)
Document format	JPEG HD resolution
Colour depth	8 bits per channel Full colour 24 bits
Colour space	RGB

tonal range and reconstruction parameters. However, the table only deals with the building blocks of the data, i.e. the images. It does not touch upon any of the other items that might be regulated, such as the technical limits of image-based methods or post-acquisition workflow. The second product is less clearly defined, namely the operative copy that would be shared and published on the web. Here, it is assumed that a second dataset must be produced, with severely truncated image attributes, in order to make a low-tier, but more manageable 3D model. In this way, the bottleneck introduced by hardware requirements for the effective manipulation of complex 3D models ('complex' here refers to highly detailed renditions) is at least partially removed. It is worth noting that when it comes to rendering 3D content – e.g. objects, interiors/exteriors and landscapes – the gaming industry has tackled the problem of the 'budget' of a 3D model, in the sense of the size and complexity that is optimal for successful handling. The most recent example is Unreal Engine 5 (Unreal Engine 2020), which boasts the capacity to store and display immensely detailed geometry with no need for extensive optimisation. Gaming-engine solutions are increasingly attracting the attention of archaeological practice (Rua and Alvito 2011; Eve 2012; Challice and Kincey 2013; Smith et al. 2019).

The master and operative copy are relevant for all other means of 3D content creation. The way in which the action is presented involves 'pre-digitalised' and 'post-digitalised' versions of the object, while the 3D scan is the intermediary between them. Any post-editing involving changes in size or the correction of geometry errors, which is highly necessary, represents a step away from the object and its original state. The digital model will henceforth be a somewhat distorted mirror of the original. Greater optimisation then takes the 3D model even further away. Due to this difference, after an object-specific threshold is reached, it will become difficult to reconnect with the original object, unless the general form is conserved. However, it will be easier to manipulate and combine several models into the same working space, introducing them into 3D editing and rendering software or preparing them for additive manufacture, and thus prolonging the life of the digital copy.

This data will be most commonly conveyed in the form of a surface model and, more often than not, a photorealistic rendition of the object. The intended use of the digital version and the technical limits of the digitising solution will determine the parameters of geometric/texture detail of the 'master' copy. The transition from master to operative copy will require further levels of engagement and a number of new iterations.

2.4 Data Management

It is frequently the case that tens of gigabytes of data in image format are required to make a model, and the master model is itself often a sizeable product. When considering scanning collections, data curation and management – including substantial storage solutions – becomes an issue for workflow planning.

By this point, it should be clear that there is a whole world of relationships between hardware, methods, project goals and outputs that should be considered when investing in 3D digitalisation. Each of the approaches creates its own file structure, which is heterogeneous across the selection and has a record track of producing repeating and perishable deliverables, where the researcher is obliged to climb a ladder of processing steps, each with its essential characteristics that might not have a place in the world after that vantage point has been superseded. A key consideration concerns what should be saved. There is a temptation to think that responsible curation requires us to save every piece of data generated, not only so that it is easy to access an old project and review all the processing decisions if something goes wrong in the process of reconstruction, but also so that, as technology develops, issues of accuracy can be revisited. This is well illustrated by the practice of testing 'old' datasets against updated versions or entirely different program solutions (Marqués 2020). Furthermore, certain objects are inherently fragile, meaning that the data used in model creation may be reutilised by other parties in the future for similar or different ends. If data from all the different stages are archived, any researcher can easily go back to a particular stage and rerun the process from that point onwards or analyse the errors and subsequently correct them, potentially with additional image editing or the introduction of additional image information. However, this comes at a hefty price, in terms of the exponentially growing intricacy of the storage strategy.

There is a sort of doomsday-preparedness logic to holding on to all the data produced in relation to the 3D digitalisation process. Creating 3D content using archaeological collections or contexts is primarily complementary to, or at least closely related to, other research objectives connected to the study of particular objects and a desire to learn more about past peoples through an object (Molloy and Milić 2018). While one of the objectives of digital models is to create objects of dissemination, the archiving principles that lie behind them are not governed by national or international policies that we are aware of and, as a result, the digital 'artefact' enters broad circulation in isolation from the source data used to create it. Since the workflow is object > data > model, the model is, in most cases, operating at a remove from the object, due to intervening decisions, and the means for critiquing this relationship or the fidelity of the model are restricted. In this sense, there is a need for a sustainable archival doctrine dictating that access be provided not just to the source files, but to the intermediate steps and the final master model, along with all of its derivates. This is an important consideration with regard to data and workflow transparency, because, at a bare minimum, the relationship between the object, the source files and the model should be archived, although arguably we also would need access to the 'thought process' which formed the model (Grimaud and Cassen 2019). Data-source specifications, autogenerated reports, software setups and the like are milestones on the path from acquisition to the 3D product. These milestones might be changed and improved upon, but understanding how one got from the object to the digital copy, which is once, twice or many times removed from the original, is paramount. Nonetheless, even when an optimised approach has been adopted, some friction can occur. Dedicated digital repositories for social-science research at UCD (University College Dublin) that were contacted by the authors (BM) were unwilling to archive the data and models, due to their large size. As a result, they are stored at the university on hard drives, a solution not considered sustainable, even when shared with the public (Breaking the mould 2015).

2.5 The Reasons for Creating 3D Models of Objects in Archaeology

The utility of 3D models in archaeological research is firmly connected to the issue of representation in archaeological science, in the sense of the way in which we choose to show the mundane and exceptional in our collections. The shortcomings of 3D models have already been enumerated. One issue is that they provide a single viewpoint, in contrast to schematic illustrations, which are capable of conveying or emphasising features of interest to a given narrative in a publication (Carlson 2014). In this sense, they are limited in their capacity to convey important details of an object without a supporting narrative or otherwise externally introduced enhancement. They are more difficult to browse than images in a collection, be it a book or a PDF. (Molloy and Milić 2018). There are also limitations in the prioritisation of the visual features and an inability to engage with the artefact using the haptic senses, i.e. the physical experience of contact (Dolfini and Collins 2018). Finally, there is also the loss of nuances of texture, taste and smell (Eve 2018).

That said, a digital rendition or a printed copy of this rendition provides the user with novel forms of engagement. In the case of objects shielded from the public by glass or held in storage in museums, they provide a substitute for direct contact. The viewer can choose how to engage with the object on their own terms and in their own time, unencumbered by space or other viewers. At the time of writing, the global Covid-19 pandemic has resulted in the unprecedented and – until a year ago – fully unexpected closure of museums around the world. Social and academic engagements have, in turn, ushered in a responsive, but also socially (if not technically) novel reliance on digital means of communication and interaction. From the classroom to the exhibition hall, conventional means of engaging with and experiencing the world have changed. As a response to a short-term scenario, many have observed how total immersion in remote interactions has made them rethink material engagements, including accessing cultural heritage *in corpore*. The Covid-19 lockdown responses will likely result in stories or published papers that will elaborate further on the potential use of 3D modelling for facilitating access to heritage spaces and places. When it comes to scientific research, models clearly boost access and engagement, with a resolution suited to several research applications. This said, the fidelity/authenticity conflict mentioned above means there is a mismatch between these new uses and the established practice of examining materials.

It may be fair to say that as a consequence of how knowledge of archaeological materials and technical steps in 3D modelling of archaeological finds are chosen, an element of artisanal skill can be recognised. This relates to preferred workflows, tips and hacks, but is not limited to them. It is a reflection of important aspects of the production of digital replicas, namely the intervention of the skilled practitioner who expedites the task (Dolfini and Collins 2018). It is through an understanding of the material, artifact or scenery, as well as what a model is intended to represent, that the relevant approach is put in place. This requires observation of the qualities of the object and an evaluation of the solutions at hand. For example, modelling a shiny surface, such as obsidian or glass, is a complex challenge and there are a range of technical solutions, from modification of the object (i.e. coating it) to lighting the object in a specific way to filter choices on the camera lens (Hallot and Gil 2019). It is important that experienced archaeological practitioners continue to provide guidance on the varieties of solutions, pipelines and outputs that deliver effective results. We see the DCHE Expert Group report (European Commission 2020), which contains tips and principles, as an important resource in this regard. The way forward appears not to involve the modeler serving as an outsourced independent technician or a solitary asset, but rather the knowledge itself being integrated into research teams from the outset. In other words, it should be done in the same way as ordinary artefact processing, with a close and comprehensive understanding of the flow of procedures and research objectives.

Let us present a case study to illustrate the potential of 3D models of artefacts in archaeology to have a post-creation afterlife in the analytical sense. In Bronze Age Europe, stone moulds were used to cast liquid bronze in order to create objects. While ceramic moulds were also in use, these are not our focus here. These moulds would go out of circulation for a variety of reasons, perhaps most obviously when they were physically broken. However, hoard deposits of stone moulds have been found in various parts of Europe which indicate that they were intentionally, not accidentally, removed from circulation for the purpose of deposition. This deliberate activity is confirmed by the frequent inclusion of both halves of two-piece moulds. Although they are not broken, we may question the expected lifecycle of such objects. Each time a casting run is conducted, there is micro-wear and tear inside the mould as a result not only of thermodynamic forces, but also of physical abrasion and degradation when the bronze object is removed from the mould. Decorative details, such as raised ribs (which are manifested in moulds as negative spaces/incisions), would eventually lose their fidelity following numerous casts. Moreover, features such as the loops in looped, socketed-axes or spearheads require spurs in the mould to create the hole corresponding to the loop. Should these be degraded or truncated, they would no longer fulfil their function. A 3D model of a mould, therefore, defines the character of that mould on the last day it was used by a smith. With a 3D model of a two-piece mould, it is possible to virtually fill in the mould, creating a positive object from the negative space. In the past, this would have been accomplished using liquid bronze, but the resolution of the digitally recreated finished object will be higher, rather than lower, because there will be no microdamage or incomplete filling of spaces. To explore this possibility, we completed a 3D model of a mould from the National Museum of Ireland, and created a positive version of it. It was immediately evident that the spaces for the decorative ribs had been degraded, and the virtual model had a relatively poor definition of these features (Fig. 2.1). From a craft perspective, it was evident that this mould was at the end of its use-life and required either rejuvenation or discard. The choice to discard this particular mould set was, therefore, arguably made because it had reached a particular stage in its lifecycle as revealed by the 3D model. Of course, this same objective could have been achieved using putty in the real mould in the

Fig. 2.1 Reconstructed positive cast of Ir the BA mould from the National Museum of Ireland, visualised in Blender. (Images acquired by Barry Molloy from the National Museum of Ireland, 3D model produced by Jugoslav Pendic, Blender 2021)

museum, but this would carry the risk of staining or otherwise tarnishing the original object. Even leaving this aside, our original reason for modelling these moulds was to compare them with other moulds, and so this re-using of the digital model reveals a potential ‘second life’, beyond the vision of the original researchers/modelers. Furthermore, a digital axe that has been created can be measured and a weight approximated on the basis of its volume. A cross-section can be extrapolated from any perspective, and an outline suited to 2D geometric morphometric analysis can also extrapolated. This points to a range of uses for the 3D model, which emerge only from the study of the digital version of an object and which are less easily undertaken with the original.

2.6 Disseminating Knowledge

Given how long 3D modelling has been widely accessible, the lukewarm response to its use in the post-scanning stage should caution us that the utility of 3D models may remain niche for the foreseeable future. That said, this is no excuse for those working in this area to not continue to develop best practices and be aware of evolving industry standards, as regards both the technical and the curation aspects of model-making. The development of effective data-management plans should be integral to this, as well as efforts to ensure, so far as is practicable, that FAIR (Findable, Accessible, Interoperable and Reusable) principles are implemented, if 3D modelling is truly to be seen as opening up access to research objects. Given the copyright status of objects in some museums or collaborative dissemination agreements, a defined strategy for dissemination (Hostettler et al., this book, Chap. 11) should be included in project designs. This is not intended as a lofty claim to signal virtue in research, but rather reflects a need to update long-established protocols for reuse and sharing, which may leave both researchers and institutions exposed to legal or moral complications. As an agenda, we believe at a personal level that the notion of 3D models being seen as a ‘democratisation’ of cultural heritage is a good thing, but that this must exist within a regulatory environment to protect all involved. The case of the unauthorised modelling and dissemination of the bust of Nefertiti in a Berlin museum (Voon 2016) is a case in point. We acknowledge that ownership of cultural property is a complex issue, but also affirm that, as professional practitioners representing our field, we bear responsibilities for the reuse of our models.

2.7 Conclusion

The fundamental issue concerns not merely the technical aspects of how to scan something using 3D technologies, but also how to responsibly manage the output. Perhaps the first step has already been made by acknowledging that 3D scanning is a complementary type of artefact study, rather than a concentrated solution that can replace previous systems for communicating archaeological objects (Horn et al. 2018; Molloy and Milić 2018). In this regard, and to conclude this paper, we identify the following points as salient:

Documenting the process of 3D content creation should be part of the analytic programme, in particular documentation of how metric data has been accurately encoded. This is needed if other users are to have confidence in the data represented by the model, which is necessary for its reuse. Moreover, this is even more relevant when multiple 3D objects are used in a comparative research workflow assessing metric or morphological relationships between objects,.

The reusability of the 3D content and its origin data is a huge gift made by the method to the research community. A single documented piece of scenery or object branches out, incorporeally, to a list of alternative use-cases: they are given form and body at the researcher's leisure. However, this raises an issue, that can easily be identified by even a layman observing from outside the milieu of archaeological and cultural-heritage management: can the ownership over the digital copy of a cultural monument or artefact with cultural property be contested and can the digital copy be protected? If we boil it down to the simplest variables, there is always a subject/item of cultural importance, with ownership claimed by the state (and probably several other stakeholders as well as), a purpose motivating the creation of digital content, a craftsperson (or craftspeople) who facilitated the process of production and an audience it was intended for. Each of these variables can be made infinitely complex, but most of them can be regulated by rigorously considering whether the caretaking institution of the physical object or mechanism wishes for exclusive rights over the product or stages of production. They may even wish to economically exploit the end outcome (Borissova 2017). One thing is, however, clear when it comes to 3D models of cultural artefacts – the only certain way to prevent their unauthorised multiplication or misuse is to not share them at all (we consider sharing in closed groups or through a paywall system to be a variation of the 'not-sharing' option).

The complexity of the workflow is currently an integral part of 3D content production in archaeology. It involves a shifting network of relationships between various industries and hardware and software development. We do not, however, consider it a battleground, but rather a challenging environment that requires preparedness, regardless of whether the 3D scanning is outsourced or incorporated into the agenda of the team/project/institution. A well-networked community of professionals – the aforementioned artisans – provide a strong foundation for moving forward on important issues related to enhancing our capacity to assess the tasks at hand, the resources available and the appropriate approaches to and quality of 3D archaeological reconstructions.

The exploration of the afterlife of 3D models and modes of reuse is key to establishing a greater degree of synchronisation in relation to this mode of documenting singular artefacts or assemblages. We presented an example in which the outcome depended on possessing a grasp of a group of skills and knowledge: how to make an accurate digital copy of the artefact via image-based methods, how to edit 3D content for viewing and processing in specialised software, and how to deliver data in order to provide an explanation for the presence of a group of artefacts in a particular archaeological context across Europe. We feel that such endeavours, in which 3D models are placed at the epicentre of research questions as tools equal to any classical ones, are the direction in which the use of 3D content to study archaeological artefacts ought to be developed.

References

Apollonio FI, Gaiani M, Benedetti B (2012) 3D reality-based artefact models for the management of archaeological sites using 3D Gis: a framework starting from the case study of the Pompeii archaeological area. J Archaeol Sci 39(5):1271–1287. https://doi.org/10.1016/j.jas.2011.12.034

Beraldin J-A, Blais F, Cournoyer L, Rioux M, El-Hakim SH, Rodella R, Bernier F, Harrison N (1999) Digital 3D imaging system for rapid response on remote sites. In: Second international conference on 3-D digital imaging and modeling, Cat. No.PR00062. IEEE Computer Society, Ottawa, pp 34–43

Blender (2021) Features. https://www.blender.org/features/. Accessed 28 Jan 2021

Bohler W, Heinz G, Marbs A (2001) The potential of non-contact close range laser scanners for cultural heritage recording. ISPRS Archives, Potsdam

Borissova V (2017) Cultural heritage digitization and related intellectual property issues. J Cult Herit 34:145–150. https://doi.org/10.1016/j.culher.2018.04.023

Boyd MJ, Campbell R, Doonan RCP, Douglas C, Gavalas G, Gkouma M, Halley C, Hartzler B, Herbst JA, Indgjerd HR, Krijnen A, Legaki I, Margaritis E, Meyer N, Moutafi I, Iliou NP, Wylie DA, Renfrew C (2021) Open area, open data: advances in reflexive archaeological practice. J Field Archaeol:1–19. https://doi.org/10.1080/00934690.2020.1859780

Breaking the mould (2015) Breaking the Mould Researching Bronze Age craft. https://sketchfab.com/breakingthemould. Accessed 28 Jan 2021

Callieri M, Dell'Unto N, Dellepiane M, Scopigno R, Soderberg B, Larson L (2011) Documentation and interpretation of an archeological excavation: an experience with dense stereo reconstruction tools, VAST: International Symposium on Virtual Reality. https://doi.org/10.2312/VAST/VAST11/033-040

Carlson ES (2014) Representation and structure conflict in the digital age: reassessing archaeological illustration and the use of cubist techniques in depicting images of the past. Adv Archaeolpract 2(4):269–284. https://doi.org/10.7183/2326-3768.2.4.269

Carvajal-Ramírez F, Navarro-Ortega AD, Agüera-Vega F, Martínez-Carricondo P, Mancini F (2019) Virtual reconstruction of damaged archaeological sites based on unmanned aerial vehicle photogrammetry and 3D modelling. Study case of a southeastern Iberia production area in the Bronze Age. Measurement 136:225–236. https://doi.org/10.1016/j.measurement.2018.12.092

Challice K, Kincey M (2013) Immersive visualization of survey and laser scanning: the case for using computer game engines. In: Opitz RS, Cowley DC (eds) Interpreting archaeological topography: 3D data, visualisation and observation. Oxbow Books, pp 238–251

Dolfini A, Collins R (2018) Modelling physical and digital replication: bridging the gap between experimentation and experience. Open Archaeol 4(1):36–49. https://doi.org/10.1515/opar-2018-0002

Dubbini M, Curzio LI, Campedelli A (2016) Digital elevation models from unmanned aerial vehicle surveys for archaeological interpretation of terrain anomalies: case study of the Roman castrum of Burnum (Croatia). J Archaeol Sci Rep 8:121–134. https://doi.org/10.1016/j.jasrep.2016.05.054

European Commission (2020) Basic principles and tips for 3D digitization of cultural heritage https://ec.europa.eu/digital-single-market/en/news/basic-principles-and-tips-3d-digitisation-cultural-heritage

Eve S (2012) Augmenting phenomenology: using augmented reality to aid archaeological phenomenology in the landscape. J Archaeol Method Theory 19(4):582–600. https://doi.org/10.1007/s10816-012-9142-7

Eve S (2018) Losing our senses, an exploration of 3D object scanning. Open Archaeol 4(1):114–122. https://doi.org/10.1515/opar-2018-0007

Granshaw SI (2018) Structure from motion: origins and originality. Photogram Rec 33(161):6–10. https://doi.org/10.1111/phor.12237

Grimaud V, Cassen S (2019) Implementing a protocol for employing three-dimensional representations in archaeology (PETRA) for the documentation of neolithic funeral architecture in Western France. Digit Appl Archaeol Cultural Herit 13:e00096. https://doi.org/10.1016/j.daach.2019.e00096

Hallot P, Gil M (2019) Methodology for 3D acquisition of highly reflective goldsmithing artefacts. Int Arch Photogramm Remote Sens Spatial Inf Sci XLII-2/W17:129–134. https://doi.org/10.5194/isprs-archives-XLII-2-W17-129-2019

Horn C, Ling J, Bertilsson U, Potter R (2018) By All Means Necessary – 2.5D and 3D recording of surfaces in the study of Southern Scandinavian Rock Art. Open Archaeol 4(1):81–96. https://doi.org/10.1515/opar-2018-0005

Huang W, Sun M, Li S (2016) A 3D GIS-based interactive registration mechanism for outdoor augmented reality system. Expert Syst Appl 55:48–58. https://doi.org/10.1016/j.eswa.2016.01.037

Jones CA, Church E (2020) Photogrammetry is for everyone: structure-from-motion software user experiences in archaeology. J Archaeol Sci Rep 30:102261. https://doi.org/10.1016/j.jasrep.2020.102261

Kahn CE, Carrino JA, Flynn MJ, Peck DJ, Horii SC (2007) DICOM and radiology: past, present, and future. J Am Coll Radiol 4(9):652–657. https://doi.org/10.1016/j.jacr.2007.06.004

Koisitinen K, Latikka J, Pontinen P (2001) The cumulative 3D data collection and management during archaeological project. In: XVIII CIPA symposium, ISPRS archives, Volume XXXIV-5/C7, Potsdam, 18–21 September, ISPRS, 2001

Koutsoudis A, Vidmar B, Arnaoutoglou F (2013) Performance evaluation of a multi-image 3D reconstruction software on a low-feature artefact. J Archaeol Sci 40(12):4450–4456. https://doi.org/10.1016/j.jas.2013.07.007

Maestri D, Canciani M, Spadafora G (2001) Archaeological survey: data processing, experimentation and direct observation. In: XVIII CIPA symposium, ISPRS archives, Volume XXXIV-5/C7, Potsdam, 18–21 September, ISPRS, 2001.

Marqués NF (2020) Old photographs for new geometries: the recent evolution of photogrammetry. https://sketchfab.com/blogs/community/old-photographs-for-new-geometries-the-recent-evolution-of-photogrammetry/. Accessed 28 Jan 2021

Martínez-Fernández A, Benito-Calvo A, Campaña I, Ortega AI, Karampaglidis T, Bermúdez de Castro JM, Carbonell E (2020) 3D monitoring of Paleolithic archaeological excavations using terrestrial laser scanner systems (Sierra de Atapuerca, Railway Trench sites, Burgos, N Spain). Digit Appl Archaeol Cultural Herit 19:e00156. https://doi.org/10.1016/j.daach.2020.e00156

McCarthy J (2014) Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. J Archaeol Sci 43:175–185. https://doi.org/10.1016/j.jas.2014.01.010

Ministarst vo culture i informisanja Republike Srbije (2017) Smernice za digitalizaciju kulturnog nasleđa u Republici Srbiji. https://www.kultura.gov.rs/extfile/sr/205/smernice-za-digitalizaciju-kulturnog-nasledja-u-republici-srbiji.pdf. Accessed 28 Jan 2021

Molloy B, Milić M (2018) Wonderful things? A consideration of 3D modelling of objects in material culture research. Open Archaeol 4(1):97–113. https://doi.org/10.1515/opar-2018-0006

Opgenhaffen L, Lami MR, Kisjes I (2018) Pottery goes public. Performing archaeological research Amid the audience. Open Archaeol 4(1):62–80. https://doi.org/10.1515/opar-2018-0004

Pakkanen J, Brysbaert A, Turner D, Boswinkel Y (2020) Efficient three-dimensional field documentation methods for labour cost studies: case studies from archaeological and heritage contexts. Digit Appl Archaeol Cultural Herit 17:e00141. https://doi.org/10.1016/j.daach.2020.e00141

Pepe M, Costantino D, Alfio VS, Restuccia AG, Papalino NM (2021) Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site. J Cult Herit 50:115–125. https://doi.org/10.1016/j.culher.2021.05.006

Pieraccini M, Guidi G, Atzeni C (2001) 3D digitizing of cultural heritage. J Cult Herit 2(1):63–70. https://doi.org/10.1016/S1296-2074(01)01108-6

Quan L (2010) Image-based modeling. Springer, New York

Remondino F (2013) Worth a thousand words – photogrammetry for archaeological 3D surveying. In: Opitz RS, Cowley DC (eds) Interpreting archaeological topography: 3D data, visualisation and observation. Oxbow Books, pp 115–122

Remondino F, El-Hakim S (2006) Image-based 3D modelling: a review. Photogramm Rec 21(115):269–291. https://doi.org/10.1111/j.1477-9730.2006.00383.x

Revello LM, Opgenhaffen L, Kisjes I (2016) Pottery goes digital: 3D laser scanning technology and the study of archaeological ceramics. In: Campana S, Scopigno R, Carpentiero G, Cirillo M (eds) CAA2015: keep the revolution going: proceedings of the 43rd annual conference on computer applications and quantitative methods in archaeology, vol 1. Archaeopress, Oxford, pp 421–431

Rua H, Alvito P (2011) Living the past: 3D models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage – the case-study of the Roman villa of Casal de Freiria. J Archaeol Sci 38(12):3296–3308. https://doi.org/10.1016/j.jas.2011.07.015

Smith M, Walford NS, Jimenez-Bescos C (2019) Using 3D modelling and game engine technologies for interactive exploration of cultural heritage: an evaluation of four game engines in relation to roman archaeological heritage. Digit Appl Archaeol Cultural Herit, e00113 14. https://doi.org/10.1016/j.daach.2019.e00113

Snavely N, Seitz SM, Szeliski R (2006) Photo tourism: exploring photo collections in 3D. ACM Trans Graph 25(3):835–846. https://doi.org/10.1145/1141911.1141964

Snavely N, Seitz SM, Szeliski R (2008) Modeling the world from internet photo collections. Int J Comput Vis 80(2):189–210. https://doi.org/10.1007/s11263-007-0107-3

Stathopoulou EK, Georgopoulos A, Panagiotopoulos G, Kaliampakos D (2015) Crowdsourcing lost cultural heritage. ISPRS Ann Photogramm Remote Sens Spatial Inf Sci II-5(W3):295–300. https://doi.org/10.5194/isprsannals-II-5-W3-295-2015

Todorov YT, Bogdanova GT, Noev N (2013) Digitization and 3D scanning of historical artifacts. Digit Present Preserv Cultural Sci Herit III:133–138

Unreal Engine (2020) A first look at Unreal Engine 5. https://www.unrealengine.com/en-US/blog/a-first-look-at-unreal-engine-5. Accessed 28 Jan 2021

Vincent M, Coughenor C (2016) Crowdsourcing the reconstruction of lost heritage. https://www.gim-international.com/content/article/crowdsourcing-the-reconstruction-of-lost-heritage. Accessed 28 Jan 2021

Vincent ML, Gutierrez MF, Coughenour C, Manuel V, Bendicho L-M, Remondino F, Fritsch D (2015) Crowd-sourcing the 3D digital reconstructions of lost cultural heritage. In: 2015 Digital Heritage. IEEE, Granada, Spain, pp 171–172

Voon C (2016) Artists covertly scan bust of Nefertiti and release the data for free online. https://hyperallergic.com/274635/artists-covertly-scan-bust-of-nefertiti-and-release-the-data-for-free-online/. Accessed 28 Jan 2021

Wahbeh W, Nebiker S (2017) Three dimensional reconstruction workflows for lost cultural heritage monuments exploiting public domain and professional photogrammetric imagery. ISPRS Ann Photogramm Remote Sens Spatial Infor Sci IV-2/W2:319–325. https://doi.org/10.5194/isprs-annals-IV-2-W2-319-2017

Wahbeh W, Nebiker S, Fangi G (2016) Combining public domain and professional panoramic imagery for the accurate and dense 3D reconstruction of the destroyed Bel temple in Palmyra. ISPRS Ann Photogramm Remote Sens Spatial Inf Sci III–5:81–88. https://doi.org/10.5194/isprs-annals-III-5-81-2016

Winkelbach S, Molkenstruck S, Wahl FM (2006) Low-cost laser range scanner and fast surface registration approach. In: Franke K, Müller K-R, Nickolay B, Schäfer R (eds) Pattern recognition. Springer, Berlin/Heidelberg, pp 718–728

Zagorchev L, Goshtasby A (2006) A paintbrushlaserrangescanner. Comput Vis Image Underst 101(2):65–86. https://doi.org/10.1016/j.cviu.2005.07.003

Chapter 3
More Than Just Documenting the Past: 15 Years of 3D Scanning at the Archaeological Heritage Office of Saxony

Florian Innerhofer, Thomas Reuter, and Conny Coburger

Abstract The 3D find documentation has been an essential part of the Archaeological Heritage Office of Saxony since 2005. The great effectiveness, the considerable gains in accuracy and the consistently high quality of the data have established the 3D laboratory as a centre of expertise. Using the three close-range scanners, over 24,000 objects had been scanned and documented by mid-2020. Various projects, such as the excavation of the Neolithic well at Altscherbitz, the DFG project 'Automated Classification' and the international, EU-funded projects on medieval mining in the Erzgebirge, clearly show the advantages of the high-resolution digitisation of archaeological finds. In addition to standard applications, industrial methods are being used to address research questions in archaeology and conservation. For example, dimensional changes during the conservation of waterlogged wooden finds are monitored by multiple scans and wear-and-tear traces are detected and examined. Furthermore, the 3D data are employed in the important area of knowledge transfer in exhibitions and public relations. With the help of common rendered graphics, animations, 3D printing and VR/AR applications, the research results and knowledge thus acquired are presented. With the publication of the Internet portal Archaeo | 3D, a platform has been created to present the 3D data from the last 15 years to both professionals and interested members of the public.

Keywords Archaeological documentation · 3D scanning · Structured-light scanning · Monitoring · Virtual archaeology · Archaeo3D

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3.1 3D Documentation of Finds

In archaeology, the visual documentation of finds has always played a decisive role in scientific discourse. Since handmade technical drawings always require a great deal of time and money, while the image obtained is always subjective, there has long been an interest in finding more efficient, cheaper and more objective technical solutions to optimise graphical documentation (Reuter and Innerhofer 2016). Even technical photography has been able to offer only limited progress in this area, due to the uncontrollable information density of photographs – individual geometric surface features are always covered by the overall texture of the photographed object. In addition, the risk of distortion and non-specified dimensional accuracy must always be compensated for (Innerhofer and Lindinger 2010).

For this reason, the Archaeological Heritage Office of Saxony (LfA Saxony) began to take an interest in the potential of 3D documentation for object-based science more than 15 years ago (Lindinger 2007; Lindinger and Hörr 2008). At that time, the industrial applications of 3D scanners were already well established and an evaluation was conducted to determine to what extent their capabilities could be used to address archaeological questions. With the acquisition of a Konica Minolta VI-910 laser scanner and the establishment of a fixed recording studio with light tent and lighting, as well as a workflow for the preparation of the 3D data (Kießling 2006), the continuous scanning of finds began. In time, the laser scanner was supplemented by two structured light scanners, which provide much more precise measurement results and present the scanned objects in considerably higher resolution (AICON smartSCAN-HE 5 MP and 8 MP; Naumann 2009) (Fig. 3.1). A further device, a mobile handheld scanner (Artec EVA™), supplements the laboratory equipment, especially when it comes to external scanning for which a high degree of flexibility and mobility is required, for example when performing detailed 3D scans in the confined galleries of medieval mines (Jahn 2013; Göttlich 2014; Reuter and Nauck 2015). All 3D scanners are equipped with colour sensors, so that the RGB data is automatically available without the need for additional recording and can be used as textures. Due to the high degree of automation and the efficiency of industrial measurement systems, Structure-from-Motion (SfM) is rarely used for the 3D digitisation of finds. Instead, it is employed for excavations or for the documentation of the archaeological features of mines.

Additionally, the program TroveSketch was developed in cooperation with the Chemnitz University of Technology, Chair of Graphic Data Processing and Visualisation, by means of which the 3D models, especially of archaeological objects, can be evaluated in a few intuitive steps (Hörr 2005, 2006, 2011). In this way, 3D models can be automatically measured and aligned with different algorithms. In addition to the usual values, such as height, width or volume, other dimensional relationships are also determined, which, after being exported to lists, can provide the basis for, e.g., training an AI application, as shown in the figure below, using the example of a pot from the Neolithic well at Altscherbitz (Fig. 3.2). Emphasis was placed on the visualisation of the 3D models using different real-time

Fig. 3.1 The Konica Minolta VI 910 laser scanner, the two AICON smartSCAN-HE structured light scanners and the Artec EVA™ handheld scanner in the 3D laboratory of the LfA Saxony. (LfA Saxony)

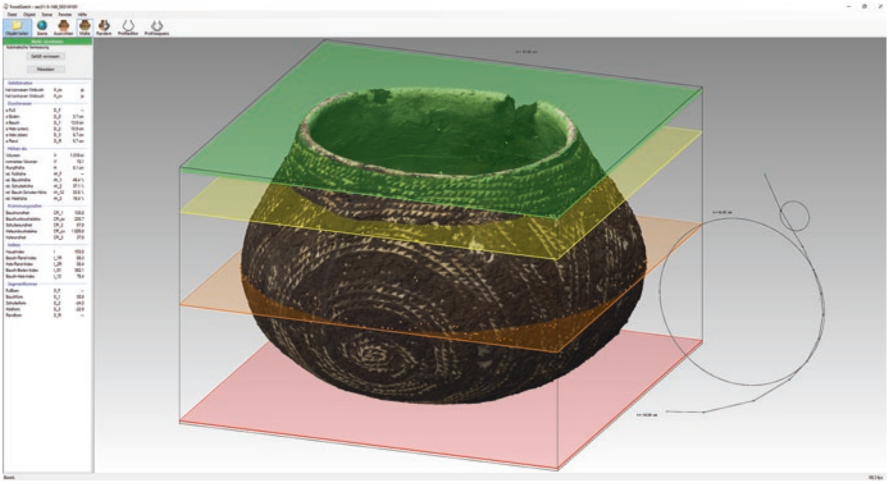


Fig. 3.2 The documentation program TroveSketch with a baggy pot from the Neolithic well at Altscherbitz. The picture shows the results and their visualisation of the automatic measurement. (LfA Saxony)

3D shaders, in order to display the scans either with the colour information or specifically in different grey or false-colour renderings, so that individual surface features, such as decorations or traces of use, can be brought out more clearly. Integrated functions for the cylindrical or polar unwrapping of rotationally symmetrical bodies, such as vessels, greatly simplify and accelerate the process of documenting complex surrounding ornaments. In a subsequent work step, the profile can then be extracted to the respective 3D model by means of freely definable sectional planes and exported as a vector graphic, enabling the generation of a complete data set of object views and associated profiles or cross-sections in a short time and with just a few clicks. The true-to-scale export of the graphics is done using common data formats. This guarantees a consistently high image quality and, for the first time, makes the find representations objectively comparable. Over the years, TroveSketch, which has undergone further stages of development, has established itself as the central interface for 3D documentation at the LfA Saxony.

Because its 3D documentation is not only accurate, but also highly effective, TroveSketch is often used by students for scanning and data processing, after a short training period, in order to document examination material for theses and dissertations (e.g. Richter 2013; Schmalfuß 2019).

3.2 Examples of Applications

On the basis of the first experiences with 3D documentation and a growing number of scanned objects, a funded research project was able to test and discuss the potential of automated classification of Late Bronze Age ceramics using 3D models (Brunnett et al. 2005; Hörr 2011; Hörr et al. 2011, 2014). The measurements and dimensional relationships of Bronze Age vessels obtained with the help of TroveSketch made it possible to classify, with a high degree of probability, precisely those shapes that had been worked out intuitively by scientific analysis using machine-learning methods.

In light of the excavation of the Neolithic well at Altscherbitz (a district in Northern Saxony) from 2008 to 2010, the scanning of archaeological waterlogged wood became a focal point for work (Elburg 2010; Tegel et al. 2012; Elburg et al. 2014; Schell and Herbig 2018). An effective workflow involving excavation, cleaning and 3D scanning made it possible to create a virtual reconstruction of the well while the excavation was taking place. This provided significant support to the excavation team's work and, through the migration of additional data, an important foundation for the archaeological documentation, as shown in the illustration (Fig. 3.3), with the cross-section of the virtual reconstruction showing the well box, the layering and the scanned vessels (Elburg et al. 2014). This enables the wooden finds to be studied while they undergo a lengthy conservation process.

Within the framework of several Interreg projects funded by the EU and carried out in cooperation with Czech partners, the experience from the excavation of the well could be exploited and further developed (e.g. Göttlich and Reuter 2013;

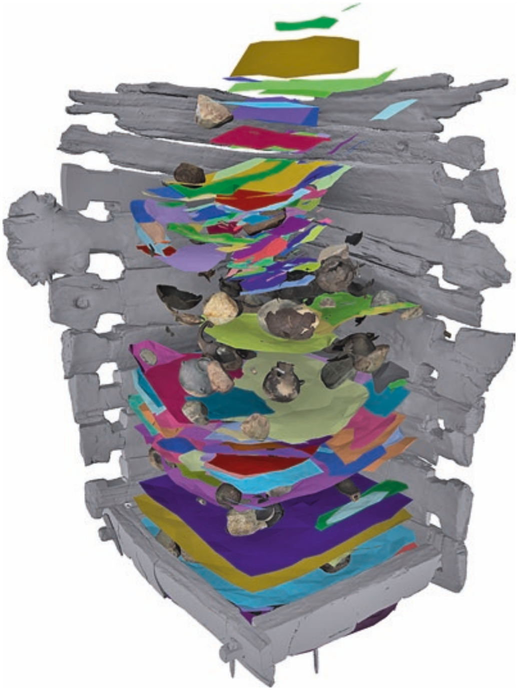


Fig. 3.3 Cross-section of the virtual reconstruction, with well box, layering and the scanned vessels. (Elburg et al. 2014)

Schröder 2018). A closely coordinated workflow between the excavation team, the conservation department and the 3D laboratory made it possible to digitise and document several thousand wooden finds. While the original wooden objects are undergoing a conservation process that will last several years, the 3D data can be used for research studies and publications. The combination of survey data, SfM and the high-resolution 3D scans makes it possible to produce detailed reconstructions, which provide a completely new approach to the excavation findings in medieval mines. A giant reversible waterwheel (fifteenth/sixteenth century), called a 'Kehrrad' in German, was found in Bad Schlema (a district in Sächsische Schweiz Osterzgebirge) at a depth of more than 30 metres and could be documented and reconstructed in detail using these methods (Drechsler et al. 2018). The massive dimensions of the wheel, with a diameter of 12 metres, made it highly challenging not only to document the excavation, which lasted more than two years, but also to manage the large amounts of data (e.g. photos, SfM, 3D scans). The targeted generalisation of the data using reverse-engineering tools, for example, reduced the high-resolution data of the structured light scanners, in order to integrate it into a virtual reconstruction (Fig. 3.4). The graphic shows the scene rendered in Autodesk 3ds max with simplified geometry blended with 3D data from the lower area, while the red circle represents the original diameter of 12 metres. The complex underground situation can thus be examined not only at the level of the finding as whole, but also at the object level by means of the original, uncompressed high-resolution 3D scans.

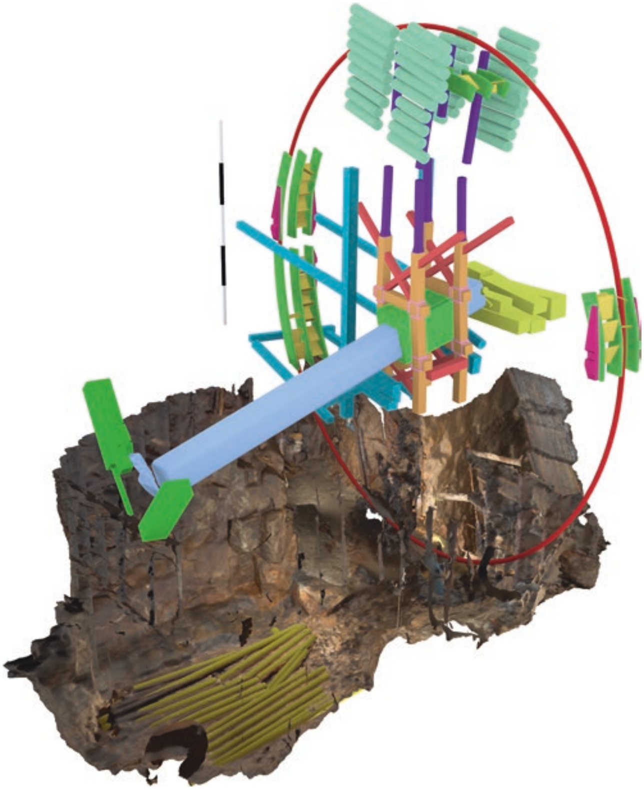
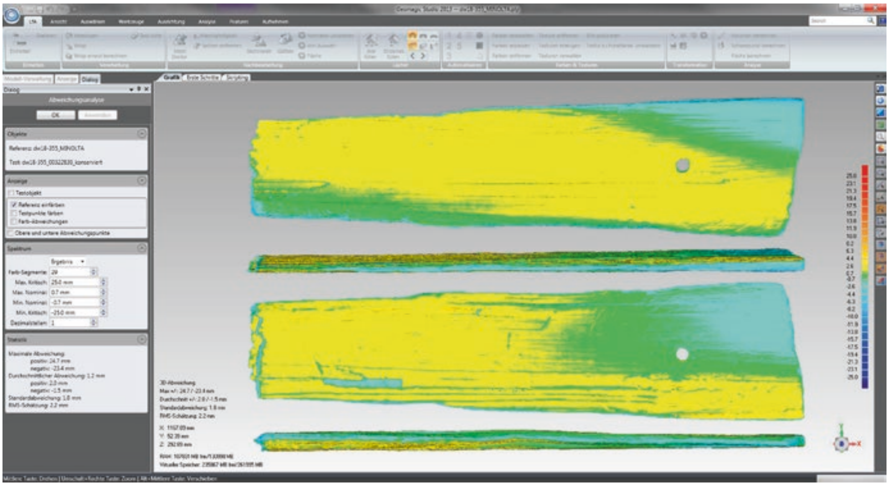


Fig. 3.4 An Autodesk 3ds max rendered scene with simplified geometry blended with 3D data from the lower area. The red circle illustrates the former diameter of 12 m of the waterwheel. (LfA Saxony)

The mass of 3D data from archaeological finds provides the data basis for further comparative measurements to detect and quantify geometric deformations of the wooden finds that inevitably occur during the conservation process, which employs impregnation and freeze-drying. Using Geomagic Studio or other appropriate software, two best-fit-aligned 3D models of an object scanned before and after conservation are compared. The result of the 3D comparison is visualised as a colour-coded texture, in which blue areas indicate shrinkage and red areas swelling (Fig. 3.5). Additional volume measurements can be used to determine the dimensions of shrinkage or swelling. These comparisons document all changes caused by internal or external influences on the object in relation to the previous measurements (Schmidt-Reimann and Reuter 2015). The results show the success of the conservation process and can serve as a basis for discussion, in order to optimise the conservation procedure if necessary. Continuous monitoring by repeated measurements is possible at any time and can be used for other objects by combining various other non-invasive, optical measuring methods (Rahrig et al. 2018).



Abweichungsanalyse

Objekte

Referenz: dw18-355_MINOLTA

Test: dw18-355_00322830_konserviert

Anzeige

☐ Testobjekt

☑ Referenz einfärben

☐ Testpunkte färben

☐ Farb-Abweichungen

☐ Obere und untere Abweichungspunkte

Spektrum

Ergebnis

Farb-Segmente: 29

Max. Kritisch: 25.0 mm

Max. Nominal: 0.7 mm

Min. Nominal: -0.7 mm

Min. Kritisch: -25.0 mm

Dezimalstellen: 1

Statistik

Maximale Abweichung
positiv: 24.7 mm
negativ: -23.4 mm
Durchschnittlicher Abweichung: 1.2 mm
positiv: 2.0 mm
negativ: -1.5 mm
Standardabweichung: 1.8 mm
RMS-Schätzung: 2.2 mm

Fig. 3.5 Deformation measurement of a wooden plank in Geomagic Studio. The point distances between the aligned reference model (original) and the test model (conserved) are projected as a texture onto the surface of the reference model with false colours (blue: shrinkage; red: swelling). (LfA Saxony)

Especially with the structured light scanners, the resolution of the 3D models of about 20 µm is so high that the 3D scans can be used for high-precision surface analyses. In particular, the quantitative documentation of traces of use opens up new research possibilities for reconstructing the history of archaeological objects. By way of example one could cite the evidence of continuous wear on a die of Varus on countermarked Roman coins from Augustan times (Tolksdorf et al. 2015, 2017). The measurement of characteristic surface features of the countermarks and the computerised classification of these features using statistical methods made it possible to develop a chronology within the test series. The figure shows the comparison of the scanned imprints made by dies in relation to edge sharpness, height and the surface quality of the embossing and changes to the inner surfaces of letters (Fig. 3.6) that, in conjunction with the origin of the coins, makes it possible to establish a plausible movement profile for Varus and his troops.

With the initial operation of a second structured light scanner, which is configured for small objects, a separate workflow was developed to scan coins, in which the very high-resolution 3D models on the front and back are mapped with additional macro photos captured by a full-frame camera. Given the rate of around 11 scanned coins per day, there are more efficient methods for digitising large quantities of coins, but these provide two-dimensional or at most 2.5-dimensional data. For example, the State Office for Heritage Management and Archaeology in Halle (Saale) employs Reflectance Transformation Imaging using an RTI-Dome to digitise and classify huge quantities of coins in high resolution. This procedure enables the reflection characteristics of the coin to be accurately captured and visualised in high resolution (Trostmann et al. 2019). However, what is missing here is precisely

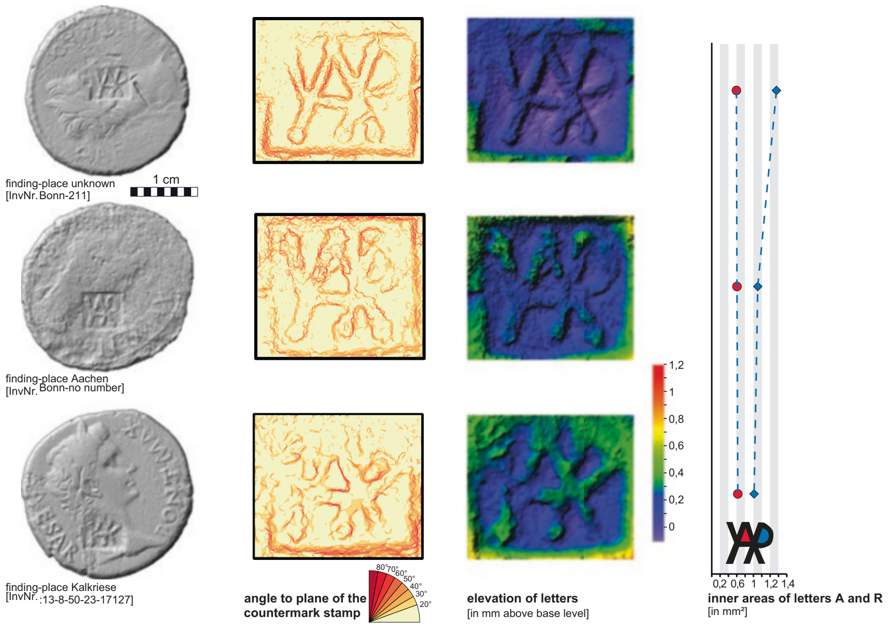


Fig. 3.6 Comparison of the scanned imprints made by dies with regard to edge sharpness, height and surface quality of the embossing and changes to the inner surfaces of letters. (Tolksdorf et al. 2015)

the third dimension that makes advanced analysis possible, as in the Varus project shown above. For this reason, the slower process of a complete 3D scan will be used in order to fully exploit the potential of the 3D data in later projects.

Coins, jewellery and flint can have shiny surfaces or be partially transparent. Ideally, these surfaces are coated with a spray to make scanning possible. In 2018, the LfA Saxony carried out investigations of various substances as part of a final thesis written in conjunction with the Dresden University of Applied Sciences (HTW). Suitability could be proven by means of recent test objects: chemical analyses of the compatibility of these substances on real archaeological surfaces of the finds are pending (Reuter et al. 2020). Similar problems occur when scanning waterlogged wood, since it is strictly forbidden to dry the surfaces or even to apply a coating. In these cases, it is necessary to consider whether the increased noise behaviour is acceptable or whether other documentation methods should be chosen. That said, experience shows that the higher information content of the 3D models compared to conventional digital photos is nevertheless clearly outweighed by slightly reduced data quality.

The documentation work that has been ongoing for many years and several parallel projects have resulted in the availability of around 24,000 3D-digitised archaeological objects from Saxony as of mid-2020, as well as finds from outside Saxony resulting from collaborations with archaeological institutions from neighbouring areas (e.g. May 2014).

3.3 Data Management

The management of 3D data during operation represents a major challenge. Each measurement initially generates raw data, in the form complex folder structures with a large number of proprietary, scanner-specific data formats, rather than individual files, as can be seen in the example of the comparison of the raw data from the AICON smartSCAN-HE and the Artec EVA™ (Fig. 3.7). Currently, all documentation data includes about 10 terabytes of storage space, which is stored on the in-house data server and backed up using suitable backup systems. For long-term archiving, the LfA Saxony will use the ExLibris Rosetta system, which currently offers only very limited support for 3D data formats and raw data and which will initially be used for other official documentation. Due to the at times very long working periods, old data is regularly requested, so that the data is currently stored, backed up and made available for direct access, but not archived using electronic long-term archiving.

Thus, it is also possible to reprocess the 3D models with different parameters at a later date or to use the raw data for texture mapping to compressed 3D models. Finally, the 3D models are exported from this recording data as Polygon File Format (*.PLY) and Wavefront (*.OBJ). These open file formats developed in the 1990s are widely used and can be read and processed by almost all 3D programs. The data servers now store 3D data from over 15 years of activity. Thanks to the consistent use of PLY and OBJ files, all 3D models can still be used and processed without any problems. However, the usability of the original raw data and measurement projects will be limited or even impossible when the proprietary scanner software is no longer used. The goal is to keep the required software running as long as possible. At the moment, LfA Saxony has not yet found a solution to this, but a strategy must be developed for dealing with the end of support for this software, as well as for the 3D scanner itself. The strategy must react to the constant developments and especially to market-driven changes.

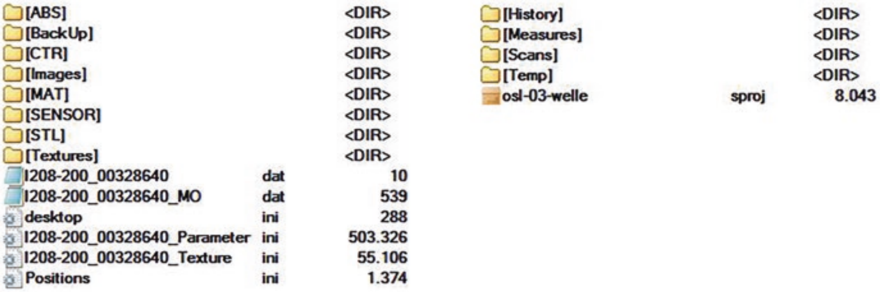


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Fig. 3.7 The comparison of the raw data from the scanner of the AICON smartSCAN-HE and the Artec EVA™. There are no similarities. (LfA Saxony)

3.4 Knowledge Transfer

Besides documentation, surface analysis, monitoring and the reconstruction of features, another important application of 3D data is the multimedia visualisation and presentation of 3D models. For a number of publications, apart from the large subject area of 3D documentation in the form of technical illustrations, the images used are no longer real photos, but rendered computer graphics (e.g. Smolnik 2014). Rendered graphics can be produced independently of a given time and location, which would be hardly or not at all possible with original objects in exhibitions or undergoing conservation, as shown by the rendered image of the grave goods of a burial (stroke pottery culture 5000–4500 BC) from Dresden-Nickern that can be seen in a permanent exhibition (Fig. 3.8). The possibilities of 3D printing have also been tested, the best examples being applications in museums. For the permanent exhibition of the State Museum of Archaeology Chemnitz (smac), for example, large exhibits, such as the Tumba of Wiprecht von Groitzsch, were produced in the original size using this process (Wolfram 2014, 186 Fig. 2; Reuter and Nauck 2015) and 3D modelling was used for object assembly (Wolfram 2014, 102 Fig. 24). In the context of museum business, replicas based on 3D printing are used for barrier-free access. The almost arbitrary scaling of 3D models allows objects to be significantly enlarged or shrunk for illustrative purposes, in order to make them more ‘comprehensible’. For example, a scaled-down 3D print of the Tumba of Wiprecht von Groitzsch is being presented at the Chemnitz State Museum of Archaeology in order to enable visually impaired visitors to experience the exhibit (Fig. 3.9).

Fig. 3.8 Rendered image of the grave goods of a burial (stroke pottery culture 5000–4500 BC) of Dresden-Nickern. (Funke et al. 2020)

Fig. 3.9 A scaled-down 3D print of the Tumba of Wiprecht von Groitzsch is used in the State Museum of Archaeology Chemnitz to make the exhibit accessible to visually impaired visitors. (LfA Saxony).

The complete 3D reconstruction of the abovementioned, approximately four-metre-high preserved linear band ceramic well at Altscherbitz, which is part of the site documentation, served as a test object for applications of virtual and augmented reality. For the VR headset Oculus Rift, the model of the Neolithic well was placed in a virtual room, which can be explored by means of user interaction and a controller (Reuter et al. 2017). In cooperation with Microsoft, a simplified 3D model of this well (ibid.), as well as other exhibits from a more than 40-metre-long showcase, could be ported to the device, enriched with additional information and visualised. (Fig. 3.10). In this augmented-reality – or more accurately mixed-reality gadget – the model is projected onto the semi-transparent glasses, seems to hover in the room and can be viewed interactively. Particularly in these applications, consideration must be given to data reduction. Techniques from game design, such as normal mapping, should be given more attention, in order to convert the highly compressed 3D models vividly even on limited hardware.

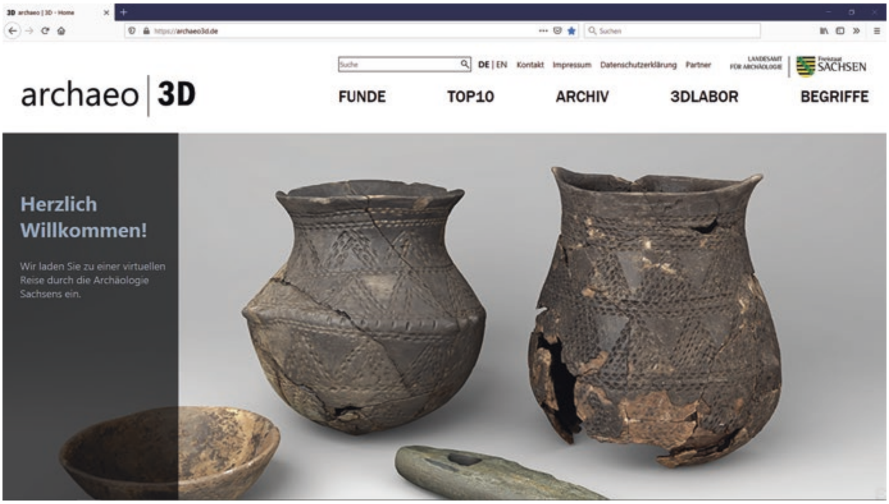
3.5 Website Archaeo | 3D

In view of the great potential of 3D data for the most diverse presentation possibilities, it was obvious that visualisation on the Internet was considered at an early stage – but as far as possible a largely 'barrier-free' one (Coburger et al. 2020). Starting from around 2010, 3D data could only be displayed with special 3D

Fig. 3.10 The exhibits from a 40-metre-long showcase in the *smac* are enriched with additional information on the Microsoft HoloLens. (LfA Saxony)

software or plug-ins for Internet browsers. With the establishment of the HTML5 standard during this period and the increasing implementation of the free JavaScript programming interface WebGL for the visualisation of 3D content in browsers, a possible solution to this requirement became apparent around 2013 (Coburger 2013). These considerations led to the creation of a comprehensive specification sheet in which the content and technical requirements for the presentation of archaeological objects on a 3D website were formulated. At the same time, however, it became clear that there was still considerable need to develop the presentation of 3D content in browsers and that the problem of transmitting relatively large amounts of 3D data via streaming was not yet fully resolved. Broadband penetration in the area of terrestrial and, above all, mobile data connections in Germany had, at the time, often not yet reached the level required to enable the smooth presentation of these data packets.

In order to keep the cost risk low in view of the many imponderables and to get the project going step by step, it was decided to draw on a pre-existing cooperation with the state-certified university Fachhochschule Dresden (FHD), particularly the Faculty of Design, for the implementation. In the winter semester 2017/2018, the design of the website was developed in the seminar ‘Interface Design’. In a user-centred design process, the students developed four comprehensive designs over the course of the semester, in which, starting from a conception of possible personas, all design elements, including typography and the colour concept for the pages and navigation, were created. Subsequently, all the proposals were evaluated and the winning proposal (Kim et al. 2018) was enriched and optimised with elements taken from the other three working groups (Böhm and Lambracht 2018; Haustein et al. 2018; Slavny et al. 2018) in around spring 2018 (Fig. 3.11). In the following



Herzlich Willkommen!

Wir laden Sie zu einer virtuellen Reise durch die Archäologie Sachsens ein.

Fig. 3.11 Welcome page of the website Archaeo | 3D. The content is available in two languages. (LfA Saxony)

semester, the programming was done in the framework of the seminar 'Basics of Web Development' at the Department of Media Informatics at the FHD. The online portal that was developed is based on the content-management system WordPress and uses the library Three.js to display the 3D models. This library offers a simplified use of WebGL, in which basic functionalities, such as displaying meshes, loading models, light effects or textures/point colours, are encapsulated in functions using JavaScript syntax, which reduces the programming workload in comparison to the low-level 3D graphics API. In order to obviate the need to manually input the archaeological metadata into WordPress, it is exported from the 3D database of LfA Saxony and imported into WordPress using WP All Import. Since the metadata is not directly transferable, it is converted using PHP scripts during this process. The plug-in Advanced Custom Fields (ACF) offers a simple way of structuring the find and metadata in WordPress and integrating it into the posts and pages.

The data generated by the 3D scanners, with their sometimes extremely high resolutions, exceed the current technical possibilities of web-based visualisation. For this reason, the original 3D models must be compressed, in order to reduce the amount of data they contain. This is inevitably accompanied by a sometimes severe loss of display quality, which must be weighed up and ultimately accepted. With the help of a test series of 3D models reduced in different ways, an upper data limit of one million polygons was found, which offers a compromise between loss of resolution, display quality and performance for the planned website. The data reduction is performed using powerful algorithms in the program Geomagic Studio. Subsequent texture mapping using the stored raw data transfers the original colour information to the simplified 3D model. Finally, the reduced 3D models are converted into the streaming file format NXS using Nexus-3D. After testing various options, the choice was made to use the tools provided by Nexus for converting PLY and OBJ files. These tools create sequences of increasingly coarse mesh partitions and simplify the geometry of the 3D model (Nxsbuild). The file sizes usually lie between 30 and 40 MB, due to the previous compression of the original models, but smaller file sizes of up to 5 MB are also possible for smaller objects, some of which do not need to be reduced at all and can be published in the original resolution.

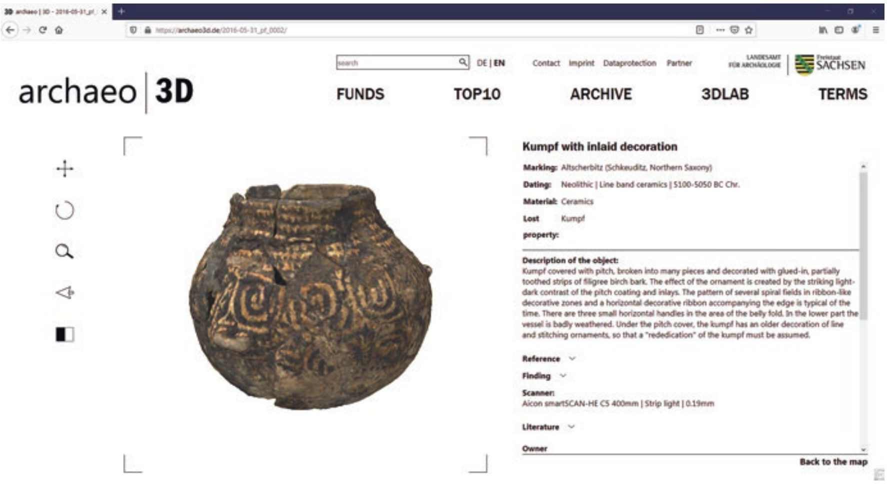
The final version was produced by the company DigitalKonstrukt and the website was published in spring 2020 at www.archaeo3d.de (e.g. the 'reconstructed grave of Niederkaina' or the 'Kumpf of Altscherbitz'). All common Internet browsers, except Internet Explorer, are supported. The consistently responsive programming makes it possible to use the website on a large number of mobile devices (Fig. 3.12). Initially about 100 finds were published and this number will steadily increase. In the future, additional functionalities will be integrated, such as a measuring function or the possibility to interactively manipulate the light source in the 3D view. For the visitor, each 3D model (i.e. each object) is linked to a unique ID number, so that all found objects remain citable via an individual and permanent web address.

The data pool can either be explored via a map display or searched using a variety of filter options. The 3D model can be viewed interactively on the corresponding object pages. The user can choose to view the objects without colour information, in order to make surface details more recognisable. Each find is supplemented with the corresponding archaeological and technical metadata. The archaeological

Fig. 3.12 Thanks to the responsive programming, the content adapts dynamically to the display size of smartphones. (LfA Saxony)

address, finding place, dating and cultural classification of the object, along with its material and category, form the core of the data set. The description of the object, as well as all information about the site, features and context of the find, the technical metadata, the literature and information on ownership and usage rights, can be found in part under expandable menu items. If there are several related objects, they are shown in the lower area with thumbnails and can be called up directly, as seen in the example of the detail page of a bark-decorated deep bowl with the 3D window on the left and the corresponding metadata on the right (Fig. 3.13). The 'Archive' page lists the thumbnails of all the objects presented on the website, while the left-hand column allows filtering across many categories. The subpage '3DLaboratory' provides comprehensive information on 3D documentation at LfA Saxony. A glossary of archaeological terms enables non-professionals to look up specialised words they may be unfamiliar with.

The technical metadata is currently being stored in the in-house 3D database. This database is based on the Archaeology Documentation and Information System of the LfA Saxony and was extended to meet the requirements of describing find objects and 3D data. In addition to the location information, which, through the administrative district, also makes it possible to link to the coordinates for presentation on a map, the archaeological address focuses on the location and type of site, the context of the features and finds, and the detailed description of the object, including dating and cultural classification. In addition, bibliographical references and proof of ownership are available, along with some technical metadata, which is intended to document the 3D acquisition. These include the sensor with the size of the measuring field and the measuring method. The resolution of the original scan can be read from the size of the point distance. There do not currently exist standards for the acquisition of technical metadata in relation to documentation with 3D



Kumpf with inlaid decoration

Marking: Altscherbitz (Schkeuditz, Northern Saxony)

Dating: Neolithic | Line band ceramics | 5100-5050 BC Chr.

Material: Ceramics

Lost property: Kumpf

Description of the object:
Kumpf covered with pitch, broken into many pieces and decorated with glued-in, partially toothed strips of filigree birch bark. The effect of the ornament is created by the striking light-dark contrast of the pitch coating and inlays. The pattern of several spiral fields in ribbon-like decorative zones and a horizontal decorative ribbon accompanying the edge is typical of the time. There are three small horizontal handles in the area of the belly fold. In the lower part the vessel is badly weathered. Under the pitch cover, the kumpf has an older decoration of line and stitching ornaments, so that a "rededication" of the kumpf must be assumed.

Reference

Finding

Scanner:
Aicon smartSCAN-HE C5 400mm | Strip light | 0.19mm

Literature

Owner

Fig. 3.13 The detail page of a bark-decorated deep bowl with the 3D window on the left and the corresponding metadata on the right. (LfA Saxony) scanners, as is usual for digital cameras with EXIF data. Therefore, this information represents a first suggestion for addressing this problem, although the automatic transfer of comparable manufacturer-specific parameters during measurement would be desirable. A comparison of the parameters in the three scanner applications used at the LfA Saxony (i.e. AICON OptoCat, Artec Studio, Geomagic Studio) shows that there are no manufacturer-specific comparable data or parameters, apart from the basic information about the manufacturer, sensor, measuring field and, finally, the resolution of the 3D model.

With this new website, the LfA Saxony has gained a powerful and expandable presentation and publication portal. If one compares the platform with traditional means of communication, such as publications or museum exhibitions, whether in analogue or digital form, it is clear that completely new paths are being taken here that allow for more direct and significantly more interactive access to the archaeological objects.

3.6 Fifteen Years of 3D Documentation

The systematic implementation of industrial measuring systems has significantly expanded the possibilities for archaeological documentation at the LfA Saxony. The expertise gained is maintained by the fact that the department is no longer a project, but is permanently integrated into the national office.It cannot be denied that the acquisition of several modern 3D scanners and the permanent operation of the scanner workplaces requires considerable financial resources. The consistently high quality and efficiency generates high-quality data, which, in the form of the standardised find graphics, are for the first time objectively comparable and do not require the experience of specialised technical draughtsmen.

With the development of TroveSketch, a simple and intuitive piece of software has been created through which traditional technical drawings can be replaced quickly, easily and with a high level of consistent display quality. With the excavation of the Neolithic well of Altscherbitz, efficient workflows were developed to salvage, clean and accurately digitalise large waterlogged organic finds in a near real-time manner. This experience was optimised within the EU-funded projects on medieval mining in the Erzgebirge, in order to make it possible to handle the find masses of several thousand pieces of wood that needed to be scanned. With their very high resolution, the structured light scanners have further developed possibilities of use in both archaeological and conservation contexts, e.g. with the detection of traces of wear and the monitoring of fragile and changing find classes.

The high-resolution 3D data, the 3D survey data and photos of the excavations are an integral part of the excavation documentation. This makes complex find situations and archaeological sites reproducible and comprehensible at any time and place. In particular, the results of the excavations, which were produced within the framework of ArchaeoMontan and the excavation of the Neolithic well at Altscherbitz, have digitally preserved the state of the site before its destruction for security reasons or before the block excavation was dismantled. As long as appropriate archives, sources and data are available, this can be scaled to almost any situation, i.e. to monuments or cultural sites that have been damaged or even destroyed by catastrophes. This shows the high value of digital archives enriched with high-quality data, which may be the only remaining source of information about damaged or even destroyed objects of any scale.

Modern web technologies, along with VR/AR applications, help communicate the information and understanding that has been acquired to the public and can provide considerable support to the transfer of knowledge. In reality, however, the originally high-resolution 3D models are usually far too large to be directly ported. Compressing and preparing the data (e.g. by mapping new textures) creates a significant workload, if the visible quality losses are to be kept within limits. The same applies to researching archaeological data for the finds to be published.

The management of the raw data, and ultimately the readability of the proprietary measurement projects, represents a major challenge for the future. The measurement data of the 3D scanners from AICON, Artec and Konica Minolta differ completely in structure and format. To keep these data readable for as long as possible, suitable solutions and procedures must be developed, because the experience of the LfA Saxony shows that even after more than 10 years, new questions can lead to a demand for the raw data. Through the consistent use of open data formats (PLY, OBJ), LfA Saxony is in a position to process all 3D models from the last 15 years without any restrictions, as many of the models that can currently be seen on the institute's Internet portal www.archaeo3d.de date back to the early years 2004/2005. The Internet portal represents an important step towards making the 3D data collected over the years and the research results obtained from them available to a broad public.

Acknowledgments We would like to thank our reviewers for their suggestions and comments. Important partners over the years include the Professorship of Computer Graphics and Visualization at the Chemnitz University of Technology, several faculties at the HTW Dresden, as well as the Faculty of Design, Dresden University of Applied Sciences. We would like to thank Bernhard Baier and Maik Ohle from the Staatsbetrieb Sächsische Informatik Dienste for the loan of an Oculus Rift, including computer, and Susann Hüttner from Microsoft for porting selected data to the HoloLens. Special thanks go to Regina Smolnik for her long-standing support. We would also like to thank our colleagues Reiner Göldner, Christoph Heiermann, Robert Reiß and Michael Strobel for their commitment over many years.

References

Böhm C, Lambracht P (2018) Dokumentation der Projektarbeit im Fach Interfacedesign. Seminararbeit, Fachhochschule Dresden

Brunnett G et al (2005) Konzept für ein System zur automatisierten Klassifikation bronzezeitlicher Gefäße. In: Paul L (ed) 3D-NordOst 2005, Tagungsband. 8. Anwendungsbezogener Workshop zur Erfassung, Modellierung, Verarbeitung und Auswertung von 3D-Daten im Rahmen der GFal-Workshop-Familie NordOst. GFaI, Berlin, pp 117–124

Coburger C (2013) Konzeption und prototypische Umsetzung einer WebGL-basierten RIA zur Unterstützung der visuellen Analyse und Präsentation archäologischer Daten. Diplomarbeit Hochschule für Technik und Wirtschaft Dresden, Fakultät Informatik/Mathematik

Coburger C et al (2020) archaeo | 3d – eine innovative Plattform zur Präsentation von archäologischen Fundobjekten im Internet. In: Smolnik R (ed) Ausgrabungen in Sachsen 7. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 34. Landesamt für Archäologie Sachsen, Dresden, pp 383–392

Drechsler G et al (2018) Ein Kehrrad aus der Zeit um 1500 – Ein Vorbericht zu den Untersuchungen eines Bergwerkes in Bad Schlema, Erzgebirgskreis. In: Smolnik R (ed) ArchaeoMontan 2018. Das Erzgebirge im Fokus der Montanarchäologie. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 32. Landesamt für Archäologie Sachsen, Dresden, pp 311–334

Elburg R (2010) Der bandkeramische Brunnen von Altscherbitz – Eine Kurzbiografie. In: Smolnik R (ed) Ausgrabungen in Sachsen 2. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 21. Landesamt für Archäologie Sachsen, Dresden, pp 231–234

Elburg R et al (2014) 3D-Funddokumentation – Ein Anwendungsbericht aus dem Landesamt für Archäologie Sachsen. In: Bienert A et al (eds) Konferenzband EVA Berlin 2014, Elektronische Medien & Kunst, Kultur und Historie. Staatliche Museen zu Berlin, pp 127–134

Funke R et al (2020) Nickern und Prohlis – Archäologie und Geschichte am Geberbach in Dresden, Archaeonaut 13. Landesamt für Archäologie Sachsen, Dresden

Göttlich F (2014) Arbeitsspuren im Altbergbau – dreidimensional dokumentiert. In: Smolnik R (ed) ArchaeoMontan 2014. Ergebnisse und Perspektiven. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 29. Landesamt für Archäologie Sachsen, Dresden, pp 81–93

Göttlich F, Reuter T (2013) Methoden der grabungsbegleitenden 3D-Dokumentation im Altbergbau. In: Smolnik R (ed) ArchaeoMontan 2012. Erkunden – Erfassen – Erforschen. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 26. Landesamt für Archäologie Sachsen, Dresden, pp 209–223

Haustein N et al (2018) Dokumentation der Projektarbeit Interaktive 3D-Webanwendung. Seminararbeit Fachhochschule Dresden

Hörr C (2005) Topologische Klassifikation archäologischer Gefäße. Studienarbeit Technische Universität Chemnitz, Fakultät für Informatik

Hörr C (2006) Segmentierung und hierarchische Klassifikation archäologischer Gefäße. Diplomarbeit Technische Universität Chemnitz, Fakultät für Informatik

Hörr C (2011) Algorithmen zur automatisierten Dokumentation und Klassifikation archäologischer Gefäße. Universitätsverlag, Chemnitz

Hörr C et al (2011) New paradigms for automated classification of pottery. In: Jerem E et al (eds) On the road to reconstructing the past. Computer applications and quantitative methods in archaeology. Proceedings of the 36th international conference, Budapest, April 2–6, 2008. Archaeolingua, Budapest, pp 268–277

Hörr C et al (2014) Machine learning based typology development in archaeology. Journal Computing and Cultural Heritage 7(1):1–23. https://doi.org/10.1145/2533988

Innerhofer F, Lindinger E (2010) Die Funddokumentation – Von der Bleistiftskizze zum 3D-Scan. In: Smolnik R (ed) Ausgrabungen in Sachsen 2. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 21. Landesamt für Archäologie Sachsen, Dresden, pp 179–183

Jahn S (2013) Vergleich von Nahbereichsscannern für die Archäologie am Beispiel des Breuckmann Streifenlichtscanners und des Eva Scanners der Firma Artec. Bachelorarbeit Hochschule für Technik und Wirtschaft Dresden, Fakultät Geoinformation

Kießling H (2006) 3D-Datenerfassung archäologischer Funde mit dem Laserscanner Konica Minolta VI-910 und Test der darauf aufbauenden Auswertesoftware. Diplomarbeit Hochschule für Technik und Wirtschaft Dresden, Fakultät Vermessungswesen/Kartographie

Kim H et al (2018) Archaeo | 3D. Website für das Landesamt für Archäologie. Seminararbeit Fachhochschule Dresden

Lindinger E (2007) Revolutionäre Entwicklung. Verbesserung der Funddokumentation dank 3D-Laserscanning. Archæo 4:36–40

Lindinger E, Hörr C (2008) Hightech meetshandmade. Ein neu entwickeltes 3D-Scanverfahren für archäologische Objekte. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. 48(49):9–18

May J (2014) Ausgeleuchtet – Die bronzenen Amphoren aus Seddin und Herzberg im Lichte neuer Dokumentationsmethoden. Arch. Berlin u. Brandenburg, pp 57–64

Naumann J (2009) Vergleich ausgewählter Nahbereichsscanner in der Archäologie. Diplomarbeit Hochschule für Technik und Wirtschaft Dresden, Fakultät Vermessungswesen/Kartographie

Rahrig M et al (2018) Opto-technical monitoring – a StandardizedMethodologytoAssessthe treatment of historical stone surfaces. Int Arch Photogramm Remote Sens Spatial Inf Sci XLII-2:945–952. https://doi.org/10.5194/isprs-archives-XLII-2-945-2018

Reuter T, Innerhofer F (2016) Mehr als bunte Bildchen – Moderne 3D-Scanner in der Funddokumentation im Landesamt für Archäologie Sachsen. Blickpunkt Arch 2016(2):105–111

Reuter T, Nauck M (2015) Wiprecht^3. Archæo 12:50–52

Reuter T et al (2017) Zurück in die Steinzeit – Ein „virtueller“ Erfahrungsbericht. In: Bienert A et al (eds) Konferenzband EVA Berlin 2017. Elektronische Medien & Kunst, Kultur und Historie. Staatliche Museen zu Berlin, pp 228–232

Reuter T et al (2020) Untersuchungen zu Mattierungsmitteln für die 3D-Digitalisierung von archäologischen Kleinfunden mit optisch schwierigen Oberflächeneigenschaften. In: Luhmann T, Schumacher C (eds) Photogrammetrie – Laserscanning – Optische 3D-Messtechnik. Beiträge der Oldenburger 3D-Tage 2020. Herbert Wichmann, Karlsruhe, pp 277–287

Richter S (2013) Das Gräberfeld von Löbnitz, Lkr. Nordsachsen. Ein Beitrag zur späten Bronzezeit in Sachsen. Arbeits- u Forschber sächs Bodendenkmalpfl 53(54):125–192

Schell F, Herbig C (2018) Ein linienbandkeramischer Brunnen im Labor. Die Ausgrabung einer Blockbergung (Bef. 3682) aus Droßdorf (Lkr. Leipzig). In: Smolnik R (ed) Ausgrabungen in Sachsen 6. Arbeits- u. Forschber. sächs. Bodendenkmalpfl. Beih. 33. Landesamt für Archäologie Sachsen, Dresden, pp 16–36

Schmalfuß G (2019) Die Befunde der Mittel- und Spätbronzezeit in den Gemarkungen Battaune, Mockrehna und Doberschütz, Lkr. Nordsachsen, unter besonderer Berücksichtigung des jüngstbronzezeitlichen Gräberfeldes Battaune. Arbeits- u. Forschber. sächs. Bodendenkmalpfl 57(58):59–164

Schmidt-Reimann P, Reuter T (2015) Conservation and 3D-documentation of waterlogged wood from medieval mining. In: Piotrowska K, Konieczny P (eds) Condition.2015 – conservation and digitalization. Conference proceedings. National Maritime Museum, Gdańsk, pp 125–130

Schröder F (2018) Funde aus mittelalterlichen Bergwerken von Niederpöbel. ArchaeoMontan 3. Veröff. Landesamt Arch. Sachsen 66. Landesamt für Archäologie Sachsen, Dresden.

Slavny A et al (2018) Archaeo3D. Projektdokumentation Interfacedesign. Seminararbeit Fachhochschule Dresden

Smolnik R (ed) (2014) Silberrausch und Berggeschrey. Archäologie des mittelalterlichen Bergbaus in Sachsen und Böhmen. Wanderausstellung des Ziel 3-Projektes ArchaeoMontan. Beier & Beran, Langenweißbach

Tegel W et al (2012) Early NeolithicWater Wells RevealtheWorld’s Oldest Wood Architecture. PLoS One 7(12):1–8. https://doi.org/10.1371/journal.pone.0051374

Tolksdorf JF et al (2015) Mit dem 3D-Scanner auf den Spuren des Varus. Archæo 12:30–33

Tolksdorf JF et al (2017) Can 3D scanning of countermarks on Roman coins help to reconstruct the movement of Varus and his legions? J Arch Sci Rep 11:400–410

Trostmann E et al (2019) Identifizierung von Münzen anhand eines digitalen Fingerabdrucks. OZeAN Online Zeitschrift zur Antiken Numismatik 1:20–27. https://doi.org/10.17879/ozean-2019-2477

Wolfram S (ed) (2014) In die Tiefe der Zeit. 300.000 Jahre Menschheitsgeschichte in Sachsen. Das Buch zur Dauerausstellung. Landesamt für Archäologie Sachsen, Dresden

Part II
Case Studies Applying 3D Technologies in Archaeology

Chapter 4

The Use and Application of SfM-Based Documentation in Excavation and Standing Remains Assessment of the Stabian Baths, Pompeii

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Abstract The international research project ‘Bathing Culture and the Development of Urban Space in Pompeii’, headed by the Institute for Classical Archaeology of the Freie Universität Berlin, uses Structure from Motion (SfM) 3D models to record, document and analyse complex archaeological and architectural situations at the Stabian Baths in Pompeii. The paper presents case studies of the application of 3D models in archaeological and architectural contexts and highlights their potential not only as a documentation method, but also as analytical tools and key aids in publishing. It also draws attention to problems arising from work with large and complex digital datasets in interdisciplinary and international research teams and suggests potential solutions.

Keywords Archaeology · Architectural survey · Building history · Pompeii · SfM documentation · Data longevity

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4.1 The Stabian Baths in Pompeii

Since 2015, a research project at the Freie Universität Berlin has been studying ‘Bathing Culture and the Development of Urban Space in Pompeii’, with a particular focus on two bathing complexes, the Republican and the Stabian Baths. Initially funded by and carried out within the framework of the German Excellence Cluster 264 Topoi (www.topoi.org/project/c-6-8/. Accessed 07 Oct 2020), since the termination of this cluster in 2019 the project has continued as a key international excavation conducted the Institute for Classical Archaeology at the Freie Universität Berlin, in cooperation with the University of Oxford (See https://www.geschkult.fu-berlin.de/e/klassarch/forschung/projekte/pompeji/index.html; https://www.topoi.org/project/c-6-8/. Accessed 07 Oct 2020). By studying the development, function and broader context of the two major early baths in Pompeii, the project seeks to provide new insights into the urban development of Republican Pompeii and the development of late Hellenistic and early Roman bathing culture (see Trümper et al. 2019).

The project encompasses excavation, full standing remains assessments and various scientific analyses of the archaeological records of both bathing complexes, including calcareous concretions from the baths, as well as wells and aquifers in their vicinity, and ash deposits. Within this framework, both digital and traditional analogue recording and documentation techniques are employed. The Republican Baths represent a traditional open archaeological site, since they no longer existed at the time of Pompeii’s destruction in AD 79 (see Trümper 2020), meaning that the extant remains can only be made visible through excavation. The Stabian Baths, by contrast, still stand largely. As a result, their study requires a highly complex process of excavation interlinked and entwined with standing remains assessments more akin to urban rescue excavations.

The sheer size and excellent state of preservation of this complex mean that traditional analogue documentation approaches frequently reach their limit, with digital methods coming to the fore. At the same time, the Stabian Baths raise specific research questions that test the limits even of digital documentation approaches. The following contribution concentrates on the potential of and problems arising from the use and application of three-dimensional documentation and data-analysis approaches in relation to the Stabian Baths – even if all of the theses and problems highlighted below are, of course, equally applicable to the Republican Baths.

4.2 Digital Methods Employed

When it comes to the application of digital documentation methods, the Stabian Baths are somewhat unique. The bathing complex has a long research history, meaning that the current project is a combination of new excavations, the re-excavation of earlier trenches and the re-evaluation of earlier archaeological work.

For the earliest archaeological excavations, see Maiuri (1932) and, for a summary, Trümper et al. (2019, 103–106). The same is true of the architectural assessment of standing remains, which by and large involves a re-evaluation of earlier work, including fundamental treatises both on the development of Pompeii as a city and of Roman bathing culture in general (Eschebach 1970, 1979; Trümper et al. 2019, 108–127). At the same time, the assessment of the standing remains requires us to not only deal with original Roman structures, but also to separate these from all the modifications and repairs carried out since their rediscovery in the mid-nineteenth century. Here, the project can draw on an analogue collection of 42 detailed drawings documenting the state of the remains of the baths during the field seasons of Hans Eschebach in the 1970s (Eschebach 1979, Plates X–XX), with some dating all the way back to the Sulze/Eschebach campaigns of the late 1930s and 40s. That said, the actual genesis of these drawings is not always clear. Some plans show varying degrees of distortion, most likely caused by a combination of changing scales, analogue field documentation and print processes. A key problem is that the widely used overall ground plan of the Stabian Baths provided by Eschebach – which is the key base plan for contextualising all the different parts of this research project – diverges from the reality of the building in many places, sometimes significantly so (Trümper et al. 2019, 108–109). Moreover, these problems do not concern only the base-state plan of the remains of the Stabian baths, since, during the project, it became evident that practically none of the reconstruction drawings provided by Eschebach actually correspond with his base plan.

This state of affairs made it necessary to take a fundamental decision about how to deal with existing plans and documentation at the outset of the project. It would have been beyond the scope of the project to completely re-document the entire complex – which measures more than 3000 m^2 and, in some areas, exhibits unique levels of preservation of both structural remains and interior decoration – either by analogue means or by modern 3D-documentation technologies. As a compromise, a new georeferenced survey grid, which is independent of the old plans, was defined for the entire site. In addition, the project is able to draw on new and georeferenced state plans generated within the framework of the 'Grande Progetto di Pompei' on the basis of 3D laserscans. These made it possible to fully correct all the existing analogue documentation elements from Eschebach's work. At key places, the corrected existing plans are supplemented with new analogue architectural drawings, 2D photogrammetries and 3D models (Fig. 4.1). While two-dimensional documentation is carried out using established methods based on total-station survey points, 3D documentation within the project is largely based on 3D photogrammetry using so-called 'Structure from Motion' (SfM).

Most of the interior walls of the men's section of the Stabian Baths have been documented using photogrammetry, in order to enable an accurate understanding of the building phases and reconstruction of their appearance (Fig. 4.2). This method suggests itself, given the fact that these walls present almost plane surfaces. It is therefore applied wherever possible to the recording of plane surfaces. In addition, the project utilises SfM wherever the geometry of the extant spaces to be documented is highly complex. The archaeological component of the project utilises

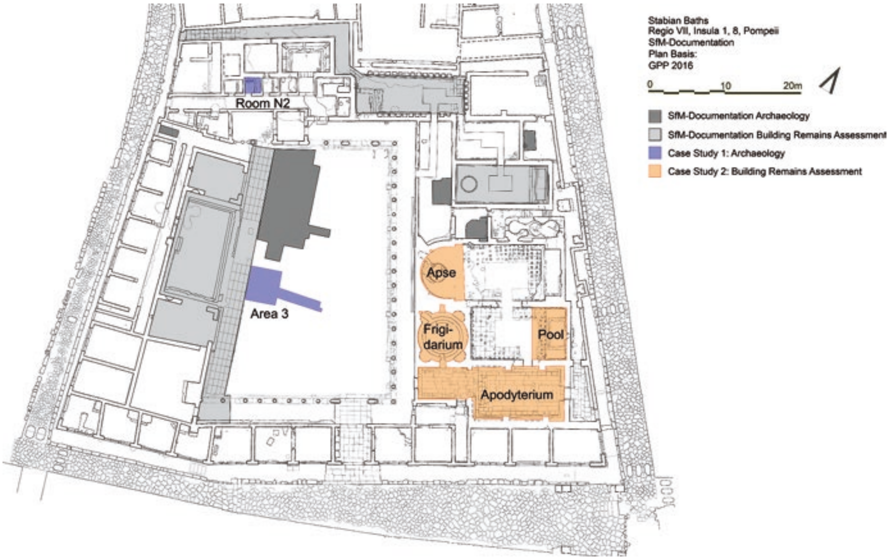


Fig. 4.1 Project state plan of the Stabian Baths. The highlighted areas show parts of the complex documented using SfM modelling and case studies presented in this paper. (C. Brünenberg, based on Eschebach (1979), pl. 2 © FU Berlin)

Fig. 4.2 Photogrammetry of the west wall of the men's *tepidarium* of the Stabian Baths. (C. Brünenberg, © FU Berlin)

SfM models as an additional means of documenting excavation trenches (with traditional analogue documentation serving as a corrective), while the architectural analyses of standing remains use SfM modelling as a basis for specific room configurations, individual spaces or specific architectural features and details. With regard to both archaeological and architectural applications, it can clearly be shown that this approach to three-dimensional documentation is ideal for highly complex spaces and geometries.

The models used to date were recorded using two different camera systems, depending on whether they are archaeological or architectural in nature – corresponding to the two teams engaged on the project. Archaeological trenches and situations were recorded using a Canon EOS 550D SLR camera with a standard EFS18–55 Canon lens, while the architectural documentation team employed a Nikon D5100 SLR with a 35 mm prime lens, also from Nikon. The models were created and calculated using AgisoftPhotoscan and, from 2019 on, its successor software AgisoftMetashape. With one exception, all the archaeological models and most of the architectural models were accurately georeferenced within the new plans of the Stabian Baths. Only the model of the pool in the men's *tepidarium* could not be georeferenced, because of its difficult local situation within an enclosed space and without stable surface to support a total station. This model was therefore referenced and scaled within a local system.

4.3 Case Study 1: Archaeology

For the excavation part of the project, traditional hand-documentation methods have been used. However, following a trial period of different digital documentation methods in the first field seasons in 2015, all of the project's trenches are now documented as 3D SfM models upon completion of each excavation season – primarily as a project-internal study tool, since they enable virtual visits to the trenches, even after backfilling or if one is not physically present at Pompeii. In several instances, the models proved to be far more than study tools and have proved instrumental for understanding the trenches during post-excavation analysis and for visualising complicated situations in publications, as the following two examples show:

One key research question concerning the Stabian Baths is the role they played in the urban development of Pompeii, as they are widely believed to cover an area previously occupied by private housing, as well as the eastern fortification of the so-called 'Altstadt' of Archaic Pompeii (Robinson et al. 2021; Trümper et al. 2019, 103–105). In order to reassess this thesis, several open areas were excavated in the *palaestra* of the baths, including Area 3 – a stratigraphic reference trench that re-opened and extended earlier excavations, connecting the remains of the baths as they are seen today in the west with the remains of an earlier house, cutting across the area where the presumed Altstadt defences would have been found (Fig. 4.3).

At its greatest extent, the resulting excavation area measured 10 × 4 m, mostly in the form of a cross-stratigraphy cut that extended to a depth of 5 m in places, across a complicated series of intercutting pits and ditches, walls, potential wells and a drain. The trench included continuous archaeological sections more than 6 m wide and 5 m tall that proved challenging for analogue documentation – particularly given that the upper levels included important features located only centimetres apart that were impossible to draw at a scale that would enable the entire section to

Fig. 4.3 Area III, a stratigraphic reference trench across the central part of the *palaestra* of the Stabian Baths, in 2016. (C. Rummel, © FU Berlin)

Fig. 4.4 Photograph of part of the S section of Area III in 2016. (C. Rummel, © FU Berlin)

fit onto paper sheets of a manageable size. It was equally difficult to document the section photographically at the relevant level of detail (Fig. 4.4) and photogrammetry had to be excluded as the drain and remains of walls disrupted the plane surfaces of the trench sections. As a result, the georeferenced 3D model of the trench provided not only a simple means of visualising the section in its entirety with the required amount of detail (Fig. 4.5), but it also proved an indispensable tool in the

Fig. 4.5 Orthophoto of the S Section of Area III, generated from the 3D SfM model. (A. Hoer, © FU Berlin, Pompeii Project)

study of this part of the archaeological record, its accuracy having been tested against analogue detail drawings. The key role of the 3D model in this particular instance is reflected in a recent project publication on the early urban development of Pompeii, which repeatedly draws on the model as a whole or sections of it as illustrations (Robinson et al. 2021, Figs. 16, 18, 21).

While this instance of 3D documentation within the archaeological component of the project was merely a means to address the problem of how to document the smallest features within a large-scale archaeological record, the Stabian Baths frequently raise challenges for archaeological documentation, given the existence of spaces containing crucial archaeological information about the development of the baths that are so small or difficult to access that traditional documentation methods cannot be employed. A case in point is a series of small rooms along a corridor in the northern tract of the baths identified as N1-N4, which had previously been interpreted as 'bathing cells' (Eschebach 1979, 51–54; Trümper et al. 2019, 110–112, 127–140), based on the observation that each of these four rooms has a sump-drain in the north-west corner, as well as a small, c. 60 cm high internal wall dividing it into a wider western and narrower eastern part (Fig. 4.6). Eschebach took the latter to be bathtubs. As this part of the Stabian Baths is of central importance for understanding their establishment and early phases, two of the rooms were excavated within the framework of the project: cell N1 was re-excavated, having been cleared by Eschebach in the 1970s; cell N2 was newly investigated (Trümper et al. 2019, 127–140).

While photographically documenting excavations of interior spaces measuring a mere 2 × 2 m was challenging, the interior dividing walls made this impossible in the smaller spaces to the east, which are only 40–56 cm wide (Fig. 4.7).

During excavation, it became apparent that in order to understand how the baths were constructed, it was important to ascertain whether or not key fill levels of Cell N2 – one of the first parts of the baths to be built – varied between the western and eastern parts of the room. As a result, it was crucial to document both archaeological sections of levels between the interior dividing wall. In the eastern section, this proved practically impossible due to the limited space available. It was, however, possible to create a full 3D model of the room using SfM on the basis of 355 individual photos (2.7 GB), with a dense point cloud of 40,215,106 points and 8,042,983

Fig. 4.6 Overview of one of the so-called 'bathing cells', room N2, from its entrance, after excavation. (C. Rummel, © FU Berlin)

Fig. 4.7 The space east of the interior dividing wall of cell N2 after excavation. (C. Rummel, © FU Berlin)

faces (Fig. 4.8). An orthophoto of the eastern face of the interior dividing wall, as well as the archaeological strata beneath it, was created from this 2.7 GB model, upon which the stratigraphic sequence could be marked in the same way as on a section drawing (Fig. 4.9). It was only through the development of the georeferenced SfM model of this space that this part of the excavated stratigraphic sequence

Fig. 4.8 SfM generated model of cell N2 of the Stabian Baths. (T. Heide, © FU Berlin)

could be visualised for the publication of this crucial dataset concerning the establishment and early development of the entire complex (Trümper et al. 2019, 138, and Figs. 15a, 15b and 17).

4.4 Case Study 2: Documenting the Interior of the Men's Section of the Stabian Baths as the Basis for an Architectural-Historical Analysis

The second case study from this project is intended to illustrate the approach, conditions and output of the SfM documentation and analysis of complicated standing remains. Within the framework of the project, it was the unique and often complex

Fig. 4.9 Vertical section orthophoto of the east face and underlying stratigraphy of the dividing wall of cell N2 with highlighted stratigraphic units. (T. Heide, © FU Berlin)

geometry of specific rooms, series of rooms or decorations of rooms that defined key parameters for 3D documentation within the framework of the assessment of standing remains. For example, the central heating furnace of the Stabian Baths, with insets for three hot water cauldrons, would have been virtually impossible to document using traditional, 2D approaches. As such, it was documented and analysed by means of a 3D model (Fig. 4.10). The main criterion for using 3D modelling as primary form of documentation was, however, an assessment of the potential added scientific value of such models on the basis of spatial analysis of the overall geometry of specific parts of the Stabian Baths.

The models presented here focus on the interior spaces of the men's tract of the Stabian Baths, which, in their final phase, consisted of four main rooms (see Fig. 4.1). From the exterior spaces, bathers entered an elongated *apodyterium* or changing room. This gave access to the round *frigidarium*, or cold bath, as well as

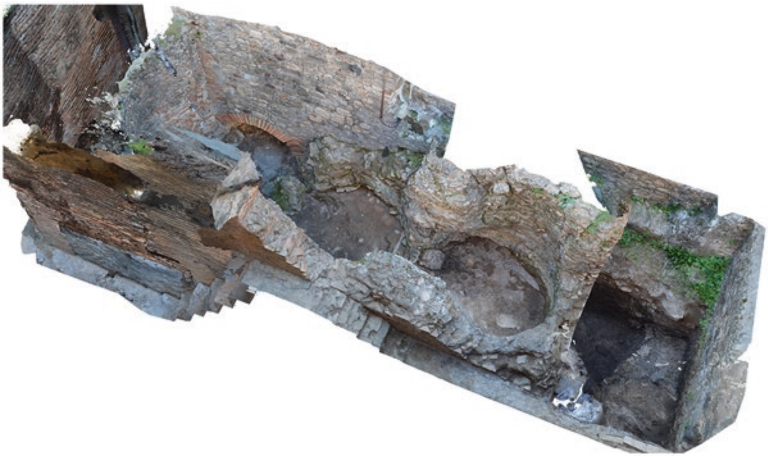


Fig. 4.10 SfM model of the central heating furnace of the Stabian Baths. (C. Brünenberg, © FU Berlin)

Fig. 4.11 Interior view of the circular *frigidarium* of the men's section of the Stabian Baths with wall decorations, SfM model. (C. Brünenberg, © FU Berlin)

the *tepidarium*, or warm room. From here, it was possible to enter the *caldarium*, or hot room. From this typical sequence of Roman bathing rooms, both the *apodyterium* and *frigidarium* were documented in their entirety as SfM models (Figs. 4.11 and 4.12). Detail models of the eastern part of the *tepidarium*, including the pool and the western apse of the *caldarium*, highlight key features of these rooms.

Different considerations informed the choice to model only parts of these rooms: in the case of the rectangular *tepidarium*, all four walls were recorded by photogrammetry. Only the eastern part of the pool and its supporting hypocaust present

Fig. 4.12 Video of the circular *frigidarium*. (C. Brünenberg)

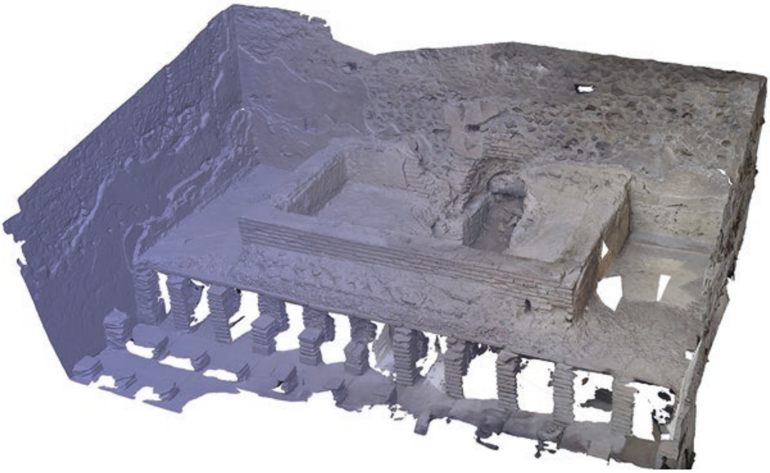


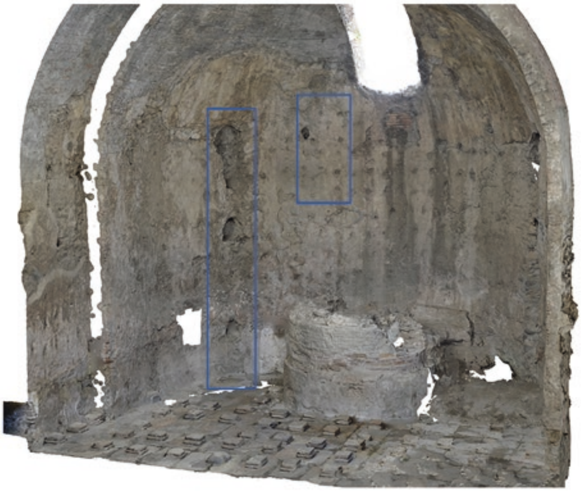
Fig. 4.13 SfM model of the pool and hypocaust heating system in the eastern part of the warm room, the *tepidarium* of the men's section of the Stabian Baths. (C. Brünenberg, © FU Berlin)

an essential and complicated 3D structure (Figs. 4.13 and 4.14). As such, documenting the room in its entirety by photogrammetry would have led to a loss of information regarding the pool and heating system due to their complex geometry, while SfM modelling would have resulted in a dataset so large it would have been difficult, if not impossible, to handle.

This resulted in a hybrid approach. The apsidal western part of the *caldarium*, with its centrally positioned *labrum*, as well as the eastern part with a large hypocaust-supported pool include complicated 3D structures. While documenting the apsidal western part did not present any problems (Figs. 4.15 and 4.16), the pool

Fig. 4.14 Video of the pool inside the men’s section *tepidarium*. (C. Brünenberg)

Fig. 4.15 SfM model of the apse at the western end of the *caldarium* of the men’s section of the Stabian Baths, including the central *labrum*. (C. Brünenberg, © FU Berlin)



and its immediate environs are extremely fragile and could only be recorded without accessing them directly, i.e. by means of an unmanned aerial vehicle or similar equipment.

A key factor in the 3D documentation approaches used in the project is ‘level of detail’ (LoD). A major aim in modelling the *apodyterium* and *frigidarium* was to produce an accurate representation of their overall spatial geometry and exact relationship to one another. To achieve this, the models were calculated to a level that accurately reflects these relationships, but that does not include every minute detail, so as to ensure the usability of the models. That said, the raw data allow for modelling at a significantly higher level of detail, if required. The other two models discussed here were created to document all remaining architectural and structural

Fig. 4.16 Video of the apse and *labrum* inside the *caldarium* in the men's section. (C. Brünenberg)

Table 4.1 Core data for the architectural models under discussion in this paper

	Documented area (L × W × H in m)	Aligned photos	Dense point cloud (Points)	Mesh (Faces)	Space requirement (GB)
Stabian Baths, *Apodyterium*		562	~270,000,000	~20,000,000	~5
Stabian Baths, *Frigidarium*	7.80 × 6.60 × 6.10	308	~170,000,000	~4,000,000	~3.7
Stabian Baths, *Tepidarium*, Pool	6.80 × 3.00 × 2.50	454	~210,000,000	~68,000,000	~9.3
Stabian Baths, *Caldarium*, Apse	7.40 × 4.80 × 7.30	394	~240,000,000	~58,000,000	~8.9

details as accurately as possible. Thus, only relevant parts were modelled in order to maintain data usability. The different purposes served by the models are directly reflected in the number of polygons (or faces) in each model, as can be seen from the core data of the four models discussed (Table 4.1).

But how exactly can such models advance our understanding and the possibilities of standing remains analyses, particularly beyond the levels achieved by traditional methods of two-dimensional documentation? The answer is to be found in the project's core research question, which can be subdivided into two categories, at least with regard to the study of the standing remains. On the one hand, the project seeks to analyse information about the materials used, the decorative programmes employed, the use of colour and other related aspects of individual rooms, as well as of the complex as a whole. These aspects can, to a large extent, be studied and analysed by means of traditional two-dimensional recording and documentation techniques. The other key aim is, however, to develop a detailed understanding of building techniques and their application in three-dimensional space, in order to be able to reconstruct building phases and processes. In concrete terms, this means that the models discussed can be interrogated in light of specific research questions:

- Stabian Baths, *frigidarium*: before this room was transformed to house the cold pool, it served as a *laconicum* (Eschebach 1979, 58–59; Trümper et al. 2019, 148–149, note 123) covered by a pointed cone roof. Eschebach describes this as '[…] konstruktiv leichter aus[zu]führen als eine Halbkugel […]. Der Konus ist über einem Lehrgerüst geformt […].' (Eschebach 1979, 59). The use of such a shoring or sub-structure during construction is highly questionable in architectural-historical terms, as it is often the very lack of such a structure that leads to a vault shape of this kind. It is only through an analysis of the overall geometry of the room and its vault that reliable and grounded architectural interpretations can be formulated with regard to this key constructional question.
- Stabian Baths, *tepidarium*, pool: one important part of the project is the reconstruction of the water supply and heating systems of the baths. The pool in the *tepidarium* is not only a key nodal point in both of these systems, but also of direct relevance for understanding the development of the baths. An analysis of the precise relationship between the pool and the eastern wall, which was broken through in order to accommodate the water supply and heating systems, as well as the surrounding hypocaust system, can provide insights into the planning and execution of these supply systems.
- Stabian Baths, *caldarium*, apse: the western part of the *caldarium* was remodelled at some point, with the west wall being dismantled to accommodate the addition of an apse. It is likely that as part of this modification, the entire room was equipped with a wall-heating system consisting primarily of *tegulae-mammatae*, tiles and spacers that created an artificial level of air along the walls of the room, as well as *tubuli*. The imprints of these spacers can still clearly be identified on the interior faces of the walls of the apse of the *caldarium* (Fig. 4.15). The precise positioning of these spacers, as well as the surviving ventilation shafts (blue highlights), make it possible to reconstruct not only the design and function of this system, but also the actual process of construction and thus its economics, i.e. the quantities of building materials involved, etc.

4.5 3D Documentation and Associated Data Beyond Field Seasons and Project Phases: Open Questions

As we have seen, 3D modelling has significant potential – and not only as a documentation tool, as it was frequently employed in the course of this project. Added scientific value can be derived from 3D models of archaeological and architectural situations, if they are correctly recorded and applied. However, models, in particular, are not necessarily easily exchanged and transferred during the evaluation phase of a project, and there are significant issues with their long-term and post-project use, publication, archiving and longevity.

Most archaeological projects have at least one common denominator, and this is also true of the project presented here: during the data-generation phase, i.e. the field seasons at Pompeii, project members are able to focus their entire attention on the object or theme of study, often on-site. The recording and documentation of study objects, including the generation of raw data for SfM modelling, is carried out on-site during these project phases. In most cases, however, post-processing of data does not occur on-site, and often it does not even occur during the field seasons. It is frequently the case that preliminary models are generated in order to minimise errors or to enable re-documentation in case problems arise. In all of the case studies presented above, the final models that were used for study and/or publication were calculated and generated only subsequently, during post-processing phases in Germany, often sometime after the field season in which the data was recorded. As the project involves a large interdisciplinary and international team (see Acknowledgements), this requires a highly structured and advanced technical workflow and exchange mechanism, enabling all the project members to access project data – whether they are based in Berlin, Oxford, Frankfurt, Darmstadt, Freiburg, Lübeck, Naples or elsewhere. This is particularly true given that, as is often the case, the technical structures of the project changed, developed and evolved over time (Trümper et al. 2019, 105) and large datasets can no longer be exchanged and transferred by traditional and direct means. At present, the project has not yet fully processed all the 3D models for which datasets have been recorded, but it is possible to present a first overview of the data involved and in use at present (Table 4.2).

The size of the data package for the processed models, at roughly 700 GB (as at 2020), may appear impressive, but it is, in fact, a normal feature of projects involving 3D documentation. The treatment of such datasets within the framework of multi-institutional cooperation projects, however, might be challenging. Should all data be stored on a single central server? Which project partner owns the rights to digital data? Do the rights remain with the relevant heritage-management bodies (as is the case in some states and countries), do they belong to the institution carrying out the research project (be they universities, research institutes or private companies) or do funding bodies, private foundations in particular, in effect ‘buy’ the rights to digital data? Moreover, which legal framework for digital data is decisive for a project with international partners? That of the lead partner?

How, then, are access rights and channels for external project members structured? Are data to be exchanged in the course of a project? If so, how are they maintained and kept updated? There are also issues that go beyond these practical

Table 4.2 Current project data amounts and requirements for SfM models

	3D Models	Dense point cloud (Points)	Mesh (Faces)	Space requirement (GB)
Stabian Baths	20	~2,500,000,000	400,000,000	450
Republican Baths	15	~1,800,000,000	200,000,000	250
TOTAL	35	~4,300,000,000	600,000,000	700

problems, such as the hardware provision of data-hosting institutions: should this be used for the calculation and generation of models at all times during projects, e.g. following software updates of key programs? In part, such problems can only be addressed by the compulsory inclusion of data-management plans in future project applications (Forschungsdatenmanagement, or FDM, in the case of German funding bodies) and their consistent application – an idealistic position that, sadly, too often succumbs to the daily realities of scientific practice.

Consistent data management and curation is of critical importance, and not only for project-internal reasons. Research and analysis rely on well-curated and well-organised datasets, but of equal significance is the question of the use and archiving of data after a project has concluded, i.e. that of the longevity of 3D data. The connected and digitised modern scientific world has made it a declared goal to archive and provide access to all relevant project data. In other words, not only the highest-resolution models are to be published, but access should be provided to all raw data, including photographs, survey points and interim states of model generation. While this will no doubt enable subsequent generations of researchers to utilise this data – either by means of new technologies or for the study of entirely new aspects – it results in even larger datasets. However, this much-vaunted goal remains, at present, just as hypothetical in nature as the hope for the sustainable implementation of data-management plans. As such, it is important to address a number of issues that are currently at best only partially resolved:

If the public availability of data is a key aim, the licensing of datasets is necessary. CC licensing offers numerous possibilities in this context, but is it a useful approach for all institutions? Independent research institutions, for example, may favour different licensing models than university libraries do (DNB 2017). However, it is the latter institutions, in particular, that represent the great hope for the long-term archiving and usability of research data in general and 3D-modelling data in particular. While such difficulties may seem academic when compared to the issue of data use in proprietary formats – at present, most of the archaeological and architectural-historical community (including this project) favour, with good reason, proprietary software from providers such as Agisoft, Autodesk and Adobe – the question remains of the issues this raises when it comes to the long-term usage and, especially, archiving of this data. A commonly advocated, but infrequently implemented solution is to require consistent archiving of the versions of programs used, in addition to the raw data (see Rimkus et al. 2014, www.forschungsdaten.info. Accessed 06 Oct 2020).

It is evident that these complex sets of problems cannot be resolved by individual projects alone. However, setting up a reasonable data and data-management structure at the outset, or ideally even in advance of a project, has now become a necessity. Depending on the size of the objects to be documented, data-management structures and workflows must be adjusted. Especially when dealing with immobile objects, such as architecture, key factors in successful documentation include: the scope of the documentation (e.g. full, sections or details), georeferencing (GPS or GCP data available), avoiding fragmentation caused by immoveable objects (e.g. vegetation) or inaccessible parts (e.g. roofs, dangerous building segments) and the classification of 3D models (e.g. walls, doors and building materials). Whilst these points apply mostly to the preparation of projects or field seasons, more general questions come to light after the initial documentation has been completed. In addition to the aforementioned problems of saving, storing and archiving 3D data, the publication of 3D data remains a contentious, unclear and largely unaddressed issue. Several proprietary platforms (e.g. Sketchfab, Agisoft) and publishers offer promising and easy solutions, but sustainability and copyright issues are often considered causes for concern. Alongside proprietary solutions, the only fully functional open-source solution at this point is 3DHOP (as at 2020), a powerful HTML-based 3D Webviewer, which was developed in Italy at the Visual Computing Lab of the Institute for Information Science and Technologies (http://3dhop.net/. Accessed 07 Oct 2020). In Germany, the Deutsche Forschungsgemeinschaft (DFG) has launched a programme to develop a sustainable national data infrastructure (NFDI: https://www.nfdi.de/. Accessed 06 Oct 2020), which represents a clear step towards creating larger overarching structures to address these issues. This programme, naturally, deals with a much larger and more fundamental issue than merely the use and application of 3D modelling data. How, then, are we to deal with this, beyond the gradual evolution of project structures, ad hoc responsive solutions and widespread capitulation in view of giant datasets?

One solution we would like to propose is the establishment and standardisation of model servers in university libraries that include multiple access points that are restricted to certain users during project periods, but open access thereafter. Such an approach would, however, necessitate the processing and curation of data while the project is running. To what extent this is feasible currently depends as much on individual choice and priorities as data exchange and international licensing do. Several initiatives, including the development of iDAIworld by German Archaeological Institute, an open-source platform tool linked to DAI-held data, ranging from images, objects, structures and collections to geographic and bibliographical data and DAI publications, as well as 3D data (see https://idai.world/. Accessed 07 Oct 2020), and dedicated archaeological programmes developed for the NFDI initiative a consortium of archaeological research institutions and universities (see https://www.nfdi4objects.net. Accessed 04 Sep 2023) are actively involved in addressing this issue and devising potential solution models, in order to provide guidelines and frameworks that can be used by individual projects.

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References

DNB (2017) Guidelines of the German National library regarding the use of Creative Commons licences. https://d-nb.info/1141694298/34. Last accessed: 06.10.2020

Eschebach H (1970) Die städtebauliche Entwicklung des antiken Pompeji. RM Suppl. 17. F.H. Kerle, Heidelberg

Eschebach H (1979) Die Stabianer Thermen in Pompeji, Denkmäler antiker Architektur, vol 13. De Gruyter, Berlin

Maiuri A (1932) Nuovi saggi di esplorazione nelle Terme Stabiane. Notizie di Scavi 1932:507–516

Rimkus K, Padilla T, Popp T, Martin G (2014) Digital preservation file format policies of ARL member libraries: an analysis. D-Lib Magazine 20(3/4). https://doi.org/10.1045/march2014-rimkus

Robinson M, Trümper M, Brünenberg C, Dickmann J-A, Esposito D, Ferrandes AF, Pegurri A, Pardini G, Rummel C (2021) Stabian Baths in Pompeii: new research on the archaic defenses of the City, accepted for Archäologischer Anzeiger, will appear in 2021

Trümper M (2020) Republican baths to Casa della Calce. A radical transformation process in Pompeii. In: Piesker K, Wulf-Rheidt U [†] (eds) Umgebaut. Umbau-, Umnutzungs- und Umwertungsprozesse in der antiken Architektur, DiskAB, vol 13. Schnell & Steiner, Regensburg, pp 11–28

Trümper M, Brünenberg C, Dickmann J-A, Esposito D, Ferrandes AF, Pardini G, Pegurri A, Robinson M, Rummel C (2019) Stabian Baths in Pompeii. New research on the development of ancient bathing culture. RM 125:103–160

Chapter 5
Defrag Memories: The 3D Spatial Analysis of the Remains of Commemorative Gestures in the Necropolis of Porta Nocera at Pompeii

François Fouriaux

Abstract The archaeological excavation carried out in 2018 by W. Van Andringa, T. Creissen and H. Duday at Porta Nocera, Pompeii, brought to light a new funerary enclosure. During the excavation, a homogeneous layer was unearthed right below the eruptive deposit layers of 79 AD. This stratum revealed several traces of occupation linked to the funerary enclosure. As the fine excavation of the artifacts proceeded, the position and form of every single fragment unearthed was methodically recorded *in situ* as a supplement to the multidisciplinary studies realised by specialists. This exceptional context of preservation enabled us to implement an innovative 3D spatial analysis of the objects and their fragmentation, in order to understand the nature and frequency of commemorative gestures at the human space-time scale. The use of digital 3D visualisation thus permits us to analyse and demonstrate the existence of certain ephemeral human acts that would otherwise not be perceived. Here, I present the method and first results, which will be integrated into a thesis directed by Prof. W. Van Andringa.

Keywords 3D analysis · Pompei · Funeral gestures · Microstratigraphy

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5.1 Studying Microstratigraphy with 3D Technologies

In trying to define what archaeology means, we usually talk about space and time, and, more specifically, about space that records past actions. In fact, human activities can be observed in the arrangement and transformation of the material world. Material witnesses (Leroi-Gourhan and Brézillon 1972, 323) to these phenomena have reached the present age thanks to different forms of conservation (in the subsoil, in architecture, in museums, etc.), whether the medium is a monument, an object, or the earth itself. Some of these material forms of evidence are direct, since they are the result of conscious constructions or modifications of matter. This is the case with inscriptions and paintings, but also with buildings and instances of destruction or rejection. By contrast, other forms of evidence are the unintentional consequences of actions, such as traces on surfaces or the seemingly random dispersion of fragments caused by a set of ritual or technical gestures or social behaviours. Through the study of these traces, archaeologists can approach a part of human history that could not otherwise be observed from other sources, even more explicit ones like texts and pictorial art. In fact, the attentive observation of traces allows us to analyse a very specific time frame, such as the slow and continuous temporality on the scale of a human life, which is not accessible in other ways. This is the temporality of gestures, which is ephemeral by nature. Here we must distinguish between the gesture (the movement of the action), the actor (the operator of the action) and the objects at work in the action (Leroi-Gourhan 1943; Mauss 1950). By studying the material traces produced by the action (in this case, the fragmentation of ceramics), it is possible to come nearer to the gesture. And through the study of the series of gestures, it is possible to come nearer to the practice of the actors in their differences and similarities (Bril 2018; Van Andringa 2021). It is therefore necessary to study the traces carefully, in their complete spatial extension, in an attempt to come nearer to the gestures and practices.

That said, archaeological methods of observation are subject to an important constraint that traditional 2D graphic documentation cannot resolve. This well-known constraint is the irreversibility of the investigative process, which makes archaeology a non-reproducible science. An archaeological site can be considered, from a geometrical point of view, as a volume made up of several entities (Harris 1997), namely the archaeological remains. In this sense, the archaeological site is an aggregate of a multiplicity of juxtaposed remains (Boissinot 2015, 14). In order to observe the relationship between the remains – and in this way understand their chronology – it is necessary to remove some of them, such that they cannot be observed afterwards. This means that, in the field, it is impossible to have a complete vision of the volume of a site, since some elements are hidden by others and others have already been irreversibly displaced by the archaeologist. Archaeologists elaborate successive views of this volume as the excavation progresses, but they never have a direct and comprehensive 3D view. Furthermore, it is necessary to individualise certain units from a continuous volume (i.e. the site), like an anatomist making a dissection (Leroi-Gourhan 1986; Balm 2016), exploring the layers one by one. In order to understand the formation of the aggregate (Boissinot 2015, 17–33) of remains, it is necessary to classify the archaeological data by shape, function, position and, finally, chronology. By creating synthetic images of the volume, 3D technologies enable us to circumvent this constraint, making it possible to see all the remains in 3D at the same time, with either a complete view or a selected view (e.g. a section), as well as to see the site in its entirety with or without classification.

For this reason, in the last few decades, digital 3D technologies have undergone significant development and been applied extensively within the field of archaeology and cultural heritage. However, this has been done almost exclusively at the scale of monuments and objects. The use of 3D has thus been focused on comprehensive 3D survey methods, like photogrammetry and laser scanning, which are used to visualise monuments (or objects) as they are today, and methods involving 3D restitution and integration into present reality, which are used to visualise monuments as they may have existed at different times in the past. In a recent development, 3D technologies have come to be seen as a research tool that is useful for exploring restitution hypotheses in bulk and for presenting and explaining the inferences underlying the scientific discourse (Ferdani et al. 2020). Archaeological remains are entities that occupy a 3D space in a way that makes it essential to compare them in a real volumetric space in order to validate proposed interpretations and restitutions. For example, an architectural restitution must harmonise with the remains observed, with the environment and with other proposed restitutions. Furthermore, 3D technologies allow us to visualise, in terms of volume, the sequences of construction, destruction and occupation at a given site. In this way, the chronology is displayed as a series of fixed pictures, i.e. of static 3D models that represent the principal phases of the site being studied.

I maintain that digital technologies are useful not only for the purposes of presentation and restitution, but also for very accurate and complex studies, such as microstratigraphic analysis, in order to arrive at a different representation of time, one that is less sequential or at least closer to lived time. This is the reason why we have developed a recording method with a 3D survey that permits us to visualise microstratigraphic phenomena that cannot be seen in any other way. This method has been employed at the necropolis of Porta Nocera at Pompeii during the most recent digging campaigns, when specific questions made necessary an original approach to spatial analysis. Both the excavation and the study are still in progress. In this paper, I present the method employed and the first results.

5.2 Studying Commemorative Gestures

In 2017, in a chapter dedicated to the various forms of memories in the context of the necropolis of Porta Nocera at Pompeii, Henri Duday and William Van Andringa emphasised the distinction between burial and funerary monuments (Duday and

Van Andringa 2017, 75). The former, *sepulcrum*, is the framework where the dead body was deposed, while the latter, *monumentum*, is the edifice built to receive commemorations of the dead. These two constructions reflect two different modalities of the constitution of funeral spaces: on one hand, the need to build a structure to receive the deceased and, on the other, the need to create a space where commemorative acts can be performed. In this text, the authors make a distinction between commemorations which are put on display, like the dedications on the front façade, and personal and private commemorations, such as acts of libation. At the end of the ceremony, and perhaps with a certain frequency after that, gestures of libations and offerings were performed, leaving *in situ* materials used during the act. For example, in sector A of the necropolis of Porta Nocera, the meticulous excavation of three enclosures has revealed the repeated association of objects, such as lamps, *unguentaria* and goblets, with the tombs (Van Andringa et al. 2013). All of them were found broken, their fragments spread on the surface of the soil, around steles that signal the position of the tomb. The recurrence of this fact makes it possible to identify an intentional and systematic deposition of these artifacts linked with the commemoration ritual. Thus, certain types of objects, selected for their function in the ritual and their symbolic value, were broken at the end of the ritual and left in place (Van Andringa 2019).

When it comes to remains of this kind, we can observe a codified ritual practice that does not serve the purpose of long-term exhibition. In fact, the demonstration is the act itself, at the moment when it is performed. The resulting traces, such as the dispersion of the fragments, are not intentional, but nonetheless constitute a testimony to the completed commemoration that we can point to and analyse several centuries later. The attentive observation of these traces permits us to ask certain questions that could not be addressed by appealing to other sources. The first set of questions concerns the temporality of these ritual commemorations. How long after the burial were these gestures performed? What was their frequency? Was it standardised or did it depend on the individual's sensibility? The second set of questions relates to variations in the accomplishment of the ritual. Were individual variants or adaptations possible within the traditional framework of the ritual codes? If so, were they dependent on the social context? And were they the result of an evolution over time?

In order to answer these questions, we assume that, on the basis of the geolocation of the artifacts, it is possible to establish the chronology of the commemorative acts beyond the relative chronology of the constitution of the tombs. We presume that the positions of objects/fragments, when discovered, coincide with their original position, or are not very far from it. Therefore, even if they are found in the same stratigraphic unit, which is commonly interpreted as an indivisible temporal block, fragments can indicate different levels of deposition, slowly covered over by natural sedimentation. In this way, we assume that, on the basis of the 3D positions of the artifacts, it is possible to reconstruct micro-events, such as libations and other offerings, that do not have a significant impact on the space.

5.3 Enter Harris's Matrix

Starting from the twentieth century, following a method of description and recording borrowed and adapted from geology, archaeologists started to pay close attention to the organisation of layers and their stratigraphic relationship (see a synthetic presentation from Lyell (1830) to Wheeler (1954) and Kenyon (1952) in Harris 1997, 1–13; Balm 2016). Activities, both human and natural, modify the surface where they happen, adding or subtracting deposit. This succession of actions leads to an accumulation of the deposit in a logical sequence that can be reconstructed by deduction on the basis of the four stratigraphic laws formulated by Harris in 1979: the law of superposition, the law of original horizontality, the law of original continuity and the law of stratigraphical succession (Harris 1997). Thus, time (i.e. the chronological succession of facts) is, in a way, encapsulated in the deposit. From the meticulous observations and classifications of archaeological remains, and specifically their relationship in space, it is possible to reconstruct the chronology of a site. Consequently, the topology of the units, i.e. their geometrical relationship in three dimensions, allows us to understand the chronological development of an archaeological site and the succession of past actions. For example, we can observe the different stages of the creation of a funeral enclosure by establishing a relationship between the wall footings, soils and different levels of occupation. An additional law, or rather principle of interpretation, is inherited from geology, namely the law of strata identified by fossils (Harris 1997). This principle presumes that materials can be used to date the layer in which they are found.

With this in mind, the archaeologists record their observations in a set of standardised documents that are useful for the description of each step of the archaeological site constitution and, by extension, the chronology of the space studied. They then organise the information in a series of statements in order to produce a sequential analysis. Given that each step in the stratigraphic chronology is characterised by a modification of the physical space, such as the construction of a wall or the deposit of a layer, we can say that this method captures each major stage of the site. In this way, it is possible to follow the development of a site over the long term and understand the succession of events.

However, if we want to investigate actions, gestures and behaviours at the scale of human life, we must deal with another challenge: time is a continuous phenomenon, and hence representing it by means of a sequential schema is not adequate for all situations. Short, everyday actions do not appear in a stratigraphic matrix, because they are found in the same layer, i.e. the same stratigraphic unit. In this way, they are not recognised as events or actions. For example, actions that are produced on the surface of a soil are not perceived, because they are all included, in the best-case scenario, in a single unit described as an occupation layer. In our case study, all the steles of the tombs, to which the commemorative acts were addressed, were progressively submerged by sedimentation. This natural phenomenon led to maintenance operations being carried out in some cases (Duday and Van Andringa 2017), but in others the steles were progressively forgotten, as they sank into the ground.

All the traces and fragments resulting from the commemorative acts are flooded in the sediment, which, from the perspective of a traditional archaeological method, should be recorded as a unique layer. In a classical stratigraphic description, all these gestures are merged into a single stratigraphical unit, in a single moment. In other words, if we want to know what happens when nothing seems to be happening at the stratigraphic level, i.e. between two significant modifications of space, we must construct a thinner chronology. It is only on this scale that we can approach the question of funerary practices, their sequences and their variations.

In fact, gestures and actions do leave some traces in the material world, from which it is possible to reconstruct their dynamism. However, traces, whether in the form of fragments of objects or the deformation of matter, are contained in something that is defined as a stratigraphic unit. From this perspective, the stratigraphic unit represents the smallest part of the site that could be analysed and placed in a chronological order, while the stratigraphic sequence is a succession of stratigraphic units, in which traces are placed on the same chronological level. In the case of the building of a wall or an embankment, we can suppose that the objects were disposed at the same time – or, more precisely, that their presence in the layer is due to the same action. However, in the case of a layer shaped by a continuous deposition, like a level of circulation or an occupational floor made of earth, we cannot reach the same conclusion. Not only is the formation of the layer slower, but it also involves objects and traces that are not made at the same time, by the same actors or through the same actions. There is a chronology that we must bring to light in order to understand the progression and frequency of actions.

The 3D digital technologies offer the opportunity to visualise and analyse *a posteriori* the site volume in its entirety on the basis of the complete documentation. In this way, a 3D document is literally a synthesis. What if this technology could be used to visualise the position of every fragment, of every artifact that filters out sediments? What if, in this way, we could identify surfaces of deposition that cannot be detected in the field because of the uniformity of the sediment? Can we enter Harris's matrix? The exceptional preservation of an enclosure discovered at Pompeii, combined with the meticulous investigation led by the research team and the sharpness of the questions formulated above, provided the opportunity to develop a 3D-based method to analyse objects in this way.

5.4 Case Study

The archaeological excavation carried out in 2018 by W. Van Andringa (École Pratique des Hautes Études, UMR 8546 AOrOc of CNRS), T. Creissen (Éveha international) and H. Duday (Université de Bordeaux, UMR 5199 PACEA of CNRS) at Porta Nocera, Pompeii, brought to light a new funerary enclosure (Fig. 5.1). During the excavation of this enclosure, which has not been disrupted by posterior occupation or by the nearby excavations conducted in 1983 (D'Ambrosio and De Caro 1987), a homogeneous layer was unearthed right below the eruptive deposit layers of 79 AD (Fig. 5.2). This stratum, which covered three steles of which only the

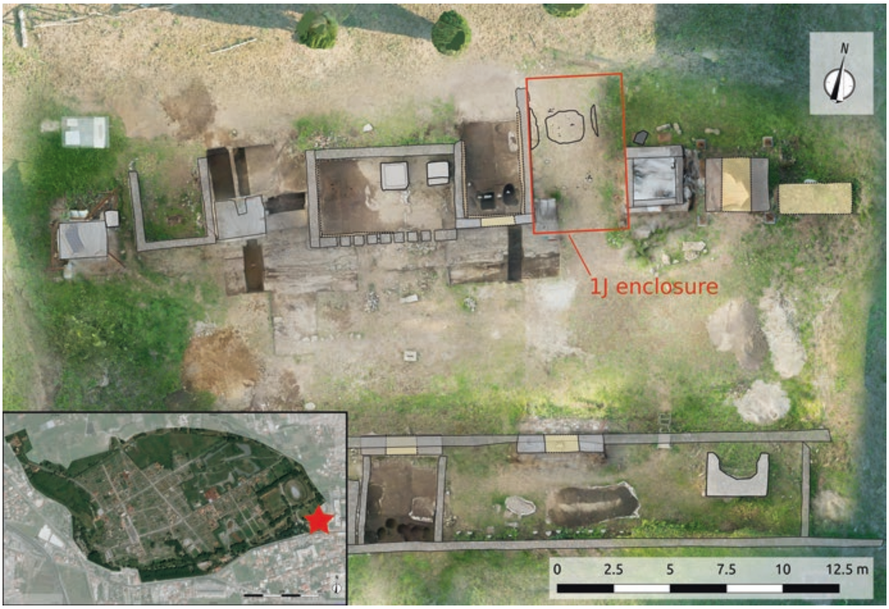

Fig. 5.1 Situation of the enclosure 1J in the necropolis of Porta Nocera/FondoPacifico

Fig. 5.2 The enclosure 1J at the time of its discovery, still covered with lapilli

Fig. 5.3 Fragments of ceramics around and against stele 2

upper part was visible after the first stripping, revealed several traces of occupation linked to the funerary enclosure, evoking other spaces of the necropolis that had been previously studied. On the surface of this stratum, a heterogeneous and highly fragmented set of materials (e.g. fragments of ceramics, glass, iron and burned bones) was found. It also presented a very particular distribution. Several concentrations of fragments belonging to the same objects (glass or ceramics) were lying around and against some funerary steles (Fig. 5.3). These steles were partially covered with homogeneous sediment, but were still visible when the aforementioned objects were dropped off. In addition, a cremation area was found in the northern part of the enclosure, which is probably linked with the three tombs.

Finally, the perfect state of preservation of this layer has given us the opportunity to develop an experimental method that makes it possible to have an extremely detailed view of the practices of funeral rites in this sector of the necropolis during the first century of our era.

5.5 Investigation and Recording Method

Faced with this particular situation, we have chosen to excavate this enclosure using a method that makes it possible to record the exact situation of each object and each object fragment. This method, inspired by A. Leroi-Gourhan (Leroi-Gourhan and Brézillon 1972), consists of releasing each artifact from the sediment and leaving the artifacts *in situ* in order to record their exact situation and layout. In order to do this, it is necessary to perform several extraction passes following the bases of objects and fragments. This method might seem highly arbitrary, but passes are also performed in a way that respects stratigraphical units. In addition, we can consider that the levels excavated in this way (i.e. following the bases of objects) best approximates the original surfaces of deposition of objects that were progressively covered by the slow, long-term sedimentation that has been observed in the necropolis of Sarsina (Ortalli 2008, 143). The application of this method in a sense places the archaeologist in the situation of the hunter guided by traces of the past, as evoked by Tim Ingold (Ingold 2013, 11).

In each pass, we conduct a georeferenced photogrammetric survey and record the position of each fragment and object (2368 units), which is packaged with an ID, inventoried and marked. To check the accuracy of the photogrammetric survey, we also recorded the position of 1151 fragments with a total station during the 2018 campaign: the standard deviation between the two data sets (mean error) is 2.8 mm, which represents half the size of the smallest collected fragments. In addition, all the sediment collected by square metre is wet-sieved through a 1 mm sieve, which makes it possible to pick up the smallest fragments and to locate them at a resolution of one square metre. Environmental studies of the sieved residues, such as carpology and anthracology, are also planned.

The second step involves putting together the fragments to reconstruct objects which are then described and studied by specialists. Links between fragments observed in this way are recorded using their ID. The result is a series of adjacency matrices (one per object), in which all the direct connections between fragments are reported. At the same time, a 3D drawing of the fragments' surfaces is performed using the orthophoto and the DTM derived from the photogrammetric model: each fragment is drawn as a vectorial polygon in QGIS from the orthophoto, then, using the DTM, we compute the altitude of each vertex with a python script that we have developed.

The next step is the realisation of a photogrammetric 3D model of objects, once the reassembly is completed. From this digital document, it is possible to isolate each fragment by cutting out the model following its shape. At the end of this operation, we have a 3D model textured with all the fragments put together. We have written an iterative script that detects the contact between fragments and thus automatically constructs the adjacency matrix. In addition, this step permits us to create a complete 3D model of each fragment and to replace the fragments at their exact location on the 3D photogrammetric model.

In doing so, all fragments, as well as the links between them, can be visualised in a GIS developed with QGIS, as a graph using the software Gephy and in a 3D model that integrates photogrammetric surveys in the software Blender (Fig. 5.4). In order to collect data in the same 3D document, it is necessary to conserve the georeferenced system, but it is difficult to manipulate these coordinates in Blender. We solved this problem by applying a simple geometrical translation to all the documents, in order to bring the data closer to the graphical origin of the software.

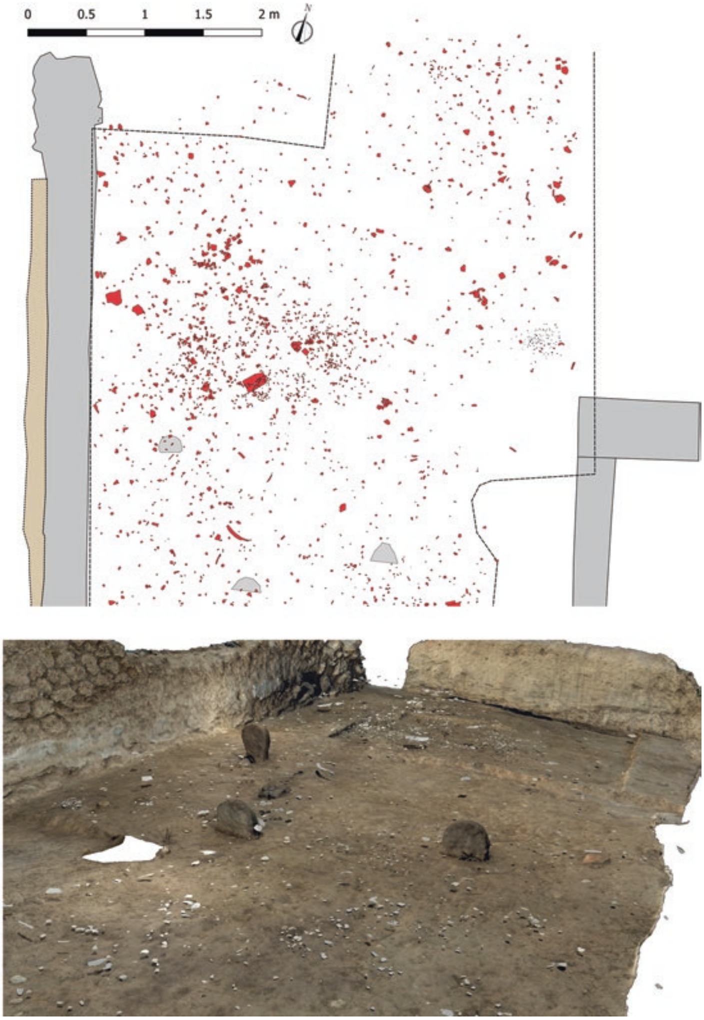

Fig. 5.4 All fragments and objects are drawn and integrated in a GIS and in a 3D model

To a certain extent, we can consider that the 3D file thus obtained is a 3D GIS where each mesh has its ID recorded as its Blender object's name. Thus, it is possible to observe in volume the surface of deposition of each object's fragment, the level of fragmentation and the dispersion of the fragments. We can also compare, in the same view, the surfaces of dispersion of several objects, and thus try to determine a microstratigraphical relationship between them: was this goblet broken and were its fragments dispersed before, at the same time or after another one?

5.6 First Results

The first result is a map that represents all the links between the fragments object by object (Fig. 5.5). This very simple visualisation allows us to see that the objects are heavily localised around certain structures, such as the steles and cremation areas. As mentioned earlier, the progressive sedimentation has submerged objects that were deposed on the surface. In this way, the position of artifacts was fixed at a certain period shortly after their deposition. The confined space in which the fragments were dispersed and the fact that some of them were positioned against steles leads us to suppose that this discovered situation is not very far removed from the initial dispersion, just after the breakage that concluded the commemorative act.

For example, the area covered by the dispersion of fragments of plate I around stela 2, is only 19.4 cm^2. It is interesting to compare the level of these first fragments with that of the steles. When we visualise our first example in 3D (Fig. 5.6), we can see that the deposition of this object occurred at a moment when the stela was already partially covered by the sediment, i.e. when the surface of the construction of the tombs was no longer visible. For the moment, it is not possible to determine how much time elapsed between the construction of the tomb and this last commemorative gesture. However, this act undoubtedly occurred a long time after the funerals, long enough for the stele to have been scarcely visible. Further excavation work will permit us to see if a commemorative act occurred just after the constitution of the tomb and, perhaps, if there were periodic acts of this type.

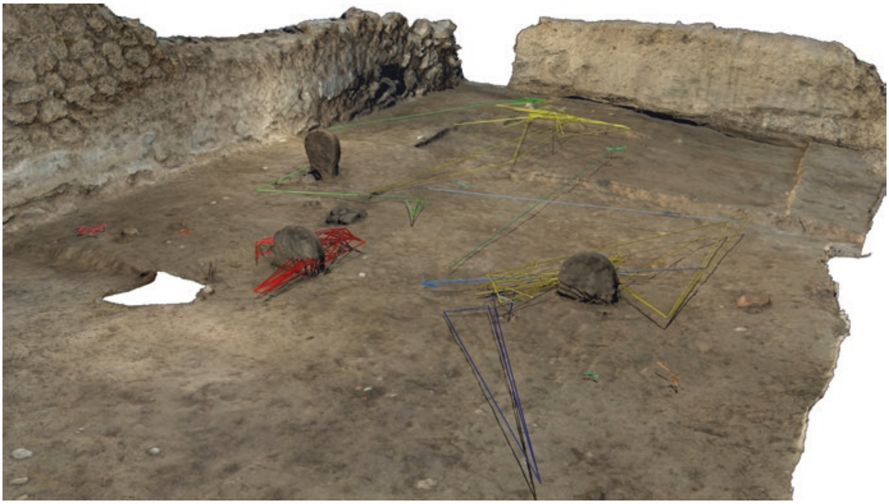

Fig. 5.5 3D representation of all the links between fragments – each colour represents a different object

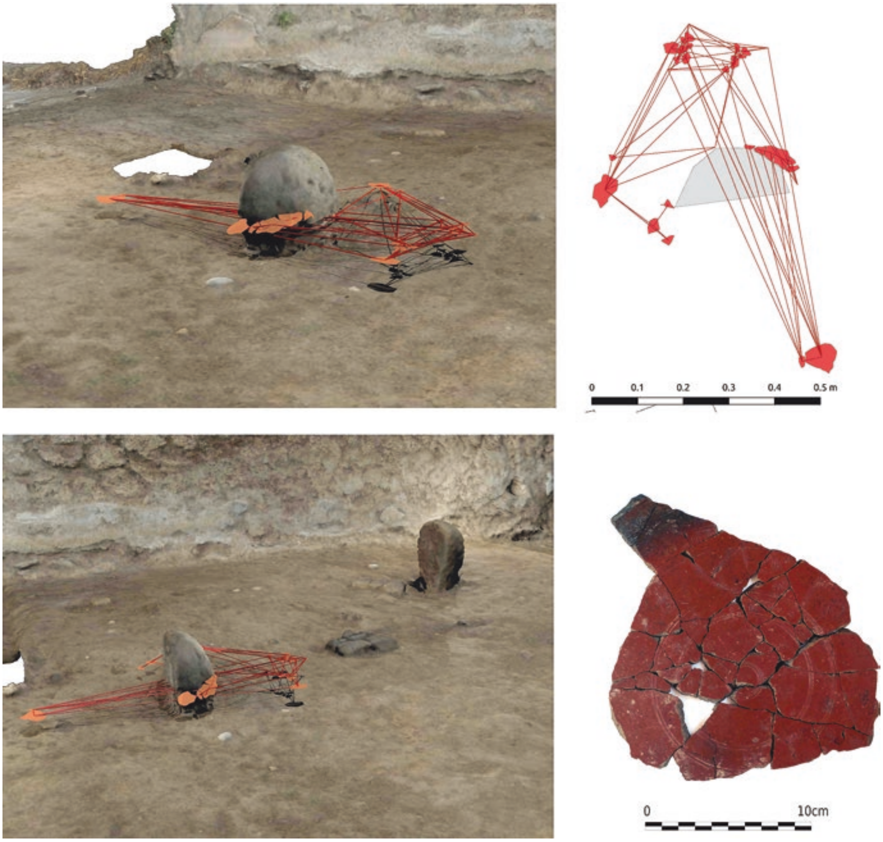

Fig. 5.6 Plan and 3D visualisation of the links between fragments of plate I around stela 2

A second example concerns the distribution of fragments around stela 3 (Fig. 5.7). Three types of object have been identified in the environment of this tomb: one goblet (Fig. 5.8), three glass balsamaries and one small ceramic bottle (unguent). The plan view of these elements shows a clear concentration around the stela, with the dispersion of few fragments at a distance of up to 1.5 metres. From a perspective view, which presents the links between fragments of each object, we can see that the deposition plans of artifacts are intertwined in a fine layer of 5 mm of sediment following the natural north–south sloping of the ground. This 3D visualisation makes it possible to detect the levels of deposition and occupation upon which the commemorative gestures took place. In addition, this digital 3D document permits us to visualise the quasi-simultaneity of the deposition of objects. Thus, we can observe the sequence of the commemoration ritual, which involves almost simultaneously the three types of objects, perhaps in an order that we will be able to determine in the future.

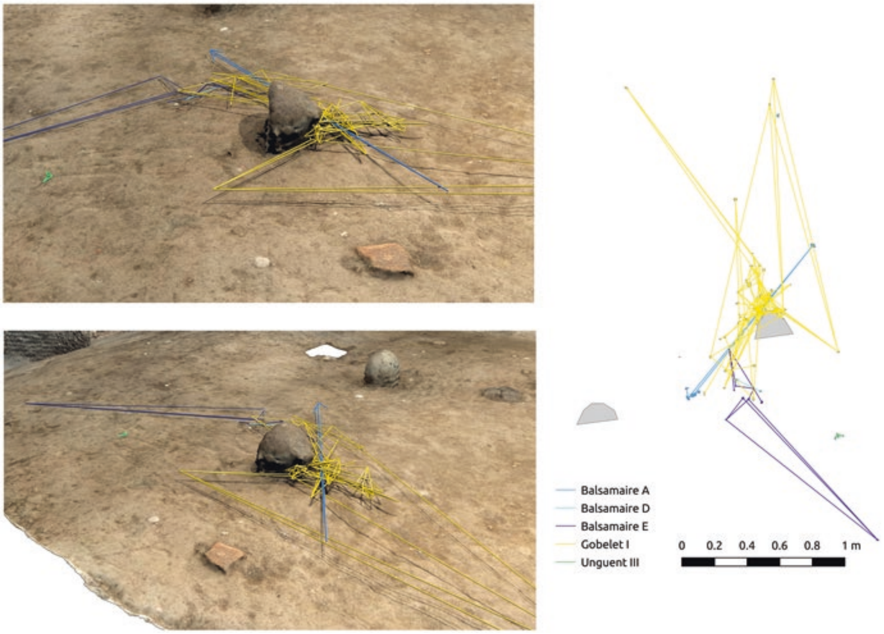

Fig. 5.7 Plan and 3D visualisation of the links between fragments by object around stela 3

Fig. 5.8 Animation showing the reconstruction of goblet 1 from the distribution of its fragments around stela 3

5.7 The 3D Reconstruction of Funerary Gestures

The exceptional context of this funerary enclosure made it possible to highlight all the subtleties of the funerary-commemoration behaviours through a study of the gestures. The method we propose allowed us to detect and document the surfaces of circulation and use of the funeral enclosure. The 3D visualisation of each of the fragments and their connections gave us the chance to show the microstratigraphy of the funeral gestures that we would not otherwise have been able to see. Without calling the Harris method into question, we believe that it is possible in some cases to go further in our stratigraphic analysis, especially by studying the three-dimensional position of fragments of objects. Our approach thus enabled to question the notion of continuous time on a human scale that is too often overlooked in archaeology. Finally, the use of 3D enabled us to visualise and display all the elements in a 3D file, with the exception of the sediment. This synthetic view was only made possible by an extremely meticulous survey and excavation method. Thanks to a highly detailed recording process, it was possible to detect and describe different funeral gestures (https://www.defragmemories.org/. Accessed: 01 Jan 2021). The excavation is still in progress, and the results of the coming years will allow us to approximate more precisely the times and frequencies of use of the enclosures of the necropolis.

References

Balm R (2016) Archaeology's visual culture: digging and desire. Routledge, Oxon

Boissinot P (2015) Qu'est-cequ'un fait archéologique? Éditions EHESS, Paris

Bril B (2018) Action, movement, and culture: does culture shape movement? Kinesiology Review. National Academy of Kinesiology and American Kinesiology Association, pp 79–87. https://doi.org/10.1123/kr.2017-0060

D'Ambrosio A, De Caro S (1987) La Necropoli di Porta Nocera. Campagna di Scavo 1983. In: Zanker P, von Hesberg H (eds) Römische Gräberstrassen: Selbstdarstellung, Status, Standard: Kolloquium in München vom 28. bis 30. Oktober 1985. Munich, pp 199–228

Duday H, Van Andringa W (2017) Arcaheology of Memory: about the forms and the time of memory in a Necropolis of Pompeii. In: Ritual matters: material remains and ancient religion. Published for the American Academy in Rome by University of Michigan Press. Knust, Jennifer Wright, pp 73–85

Ferdani D, Demetrescu E, Cavalieri M, Pace G, Lenzi S (2020) 3D modelling and visualization in field archaeology. From survey to interpretation of the past using digital technologies. Groma Doc Archaeol 15. https://doi.org/10.12977/groma26

Harris EC (1997) Principles of archaeological stratigraphy, 2. ed., 3. print. Acad. Pr, London

Ingold T (2013) Making: anthropology, archaeology, art and architecture. Routledge/London, New York

Kenyon KM (1952) Beginning in archaeology. Phaeonix House Limited, London

Leroi-Gourhan A (1943) L'homme et la matière. Albin Michel, Paris

Leroi-Gourhan A (1986) Le fil du temps: ethnologie et préhistoire. Fayard, Paris

Leroi-Gourhan A, Brézillon MN (1972) Fouilles de Pincevent: essai d'analyse ethnographique d'un habitat magdalénien. 2, Plans. Éditions du C.N.R.S, Paris

Lyell C (1830) Principles of geology. John Murray, London
Mauss M (1950) Sociologie et antrhopologie. Presses universitaires de France, Paris
Ortalli J (2008) Scavostratigrafico e contestisepolcrali. In: Pour unearchéologie du rite: nouvelles perspectives de l'archéologiefunéraire. École française de Rome, Rome, pp 137–159
Van Andringa W (2019) Rituels pour les morts et culte des dieux à Pompéi. In: Jouanna J, Vauchez A, Scheid J, Zink M (eds) Cahiers de la villa Kérylos. Académie des Inscriptions et Belles-Lettres, Paris, pp 99–119
Van Andringa W (2021) Archéologie du geste: rites et pratiques à Pompéi. Hermann, Paris
Van Andringa W, Duday H, Lepetz S, Joly D, Lind T (2013) Mourir à Pompéi: fouille d'un quartier funéraire de la nécropole romaine de Porta Nocera: 2003–2007. École française de Rome, Rome
Wheeler M (1954) Archaeology from the earth. Clarendon Press, Oxford

Part III
Pushing the Boundaries: New Research Questions

Chapter 6
Rock Art in Three Dimensions: Comments on the Use and Possibilities of 3D Rock Art Documentation

Christian Horn, Mark Peternell, Johan Ling, Ashely Green, and Rich Potter

Abstract Methods to document rock art in all three dimensions have become a standardized workflow. In this article, we discuss their advantages and disadvantages when compared to older reductive approaches to rock art documentation. Furthermore, some misunderstandings regarding 3D documentation are addressed. As the majority of the problems presented by the 3D documentation of rock art can be solved through advanced visualization workflows, recent developments in this area are described. The rock art documentation described in this contribution also serves wider research purposes, which will be discussed. Newly discovered images and newly developed machine learning algorithms will also be introduced.

Keywords Laser scanning · Structure from motion · Visualization · Machine learning · Rock art · Bronze age · Scandinavia

6.1 Introduction

The strong push to make image and range-based 3D recording the standard methods of documenting rock art has largely been successful in hindsight. The best evidence for the overall scientific acceptance has been the successful granting of several large digitization projects concerned with rock art in Italy, Great Britain, Iberia, and Scandinavia. The material that is digitized is diverse in technique and chronology,

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dating from the Neolithic and the Bronze Age to medieval picture stones and later expressions of human creativity on rock (Alexander et al. 2015; Díaz-Guardamino et al. 2019; Díaz-Guardamino Uribe and Wheatley 2013; Foster et al. 2016; Horn and Potter 2019; Höll et al. 2014; Noble and Brophy 2011; Oehrl 2020). While this seems like a success story, reluctance and misconceptions still surround the 3D documentation of rock art. However, proponents of 3D documentation should be open to concerns about problematic aspects of these methods. This is not only an issue of academic ethics, but also that it helps us to address these problems and advance our methods. Baseline method development is often treated as somewhat of a black sheep by funders and researchers who are both often just looking forward to the next earth-shattering discovery rather than the baseline work that enables such discoveries. This neglect is the reason why the "third science revolution" in archaeology was driven by fields outside of archaeology and had very little initial involvement from archaeology (Kristiansen 2014). It is also the reason why many archaeologies and archaeologists are just now catching up with debates that should have been present at the onset of the developing methods – as best illustrated by the contentious discussion around aDNA (Frieman and Hofmann 2019; Furholt 2019; Pääbo et al. 2004).

In the following, we will discuss the advantages of 3D documentation compared to reductive, traditional methods by reviewing some of the misconceptions. We will also discuss the problems that exist with 3D documentation, and finally, outline some future directions regarding how 3D recordings of rock art could be used to accommodate some of the problems and drive forward future research. The following remarks will only address rock art during the Nordic Bronze Age (1800/1700–550 BC) which was produced by a percussive technique removing material from the rock surface to produce a negative relief (Fig. 6.1). Although not technically correct in most cases, the images are called carvings. We will keep this term and use it interchangeably with the term petroglyph. We will give the inventory numbers of the Swedish National Heritage Board for each rock art panel we discuss.

6.2 2D and 3D Rock Art Recording

In the best of cases, petroglyphs are several millimetres deep and are visually perceptible. However, most carvings are very shallow either through weathering and other erosion (Robinson and Williams 1994; Sjöberg 1994; Swantesson 2005), or because they were initially not carved very deeply. The latter may seem counterintuitive, because why would people have made images which they then could not clearly see. Freshly produced rock art removes part of the weathered rock surface which makes it show up lighter than the surrounding areas. This means that the images would have been visible to observers for at least a few years even if they were very shallow. A carving in Lyse (L1969:9961; Lyse 142:1) was discovered on a vertical surface protected from weathering by an overhang, which still has some

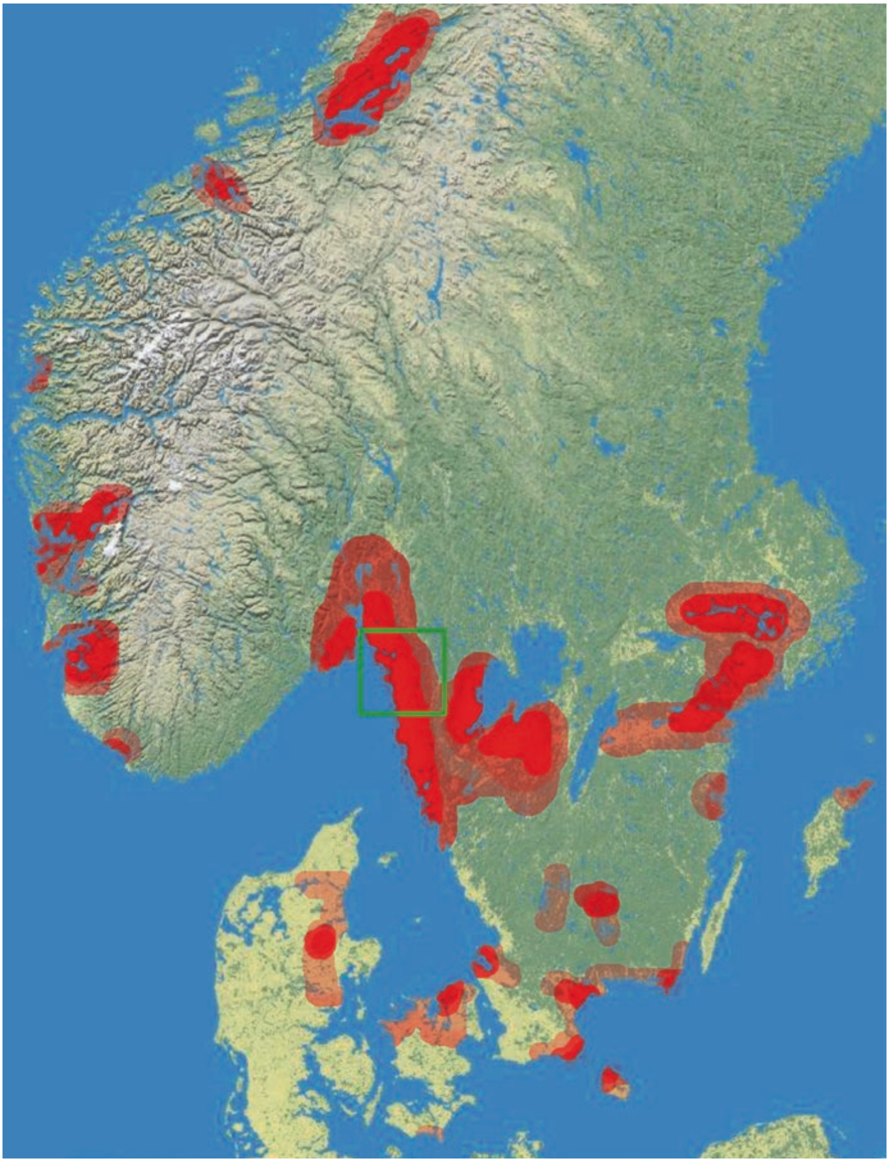

Fig. 6.1 Rock art distribution in southern Scandinavia (green square: main study area)

of its lighter appearance preserved. Experiments in carving rock art (Bengtsson 2004; Lødøen 2015) and even modern vandalism show that rock carvings are lighter than the surrounding rock (Fig. 6.2). Due to the problematic visibility and continuous erosion of rock art, documentation methods have always strived to be as holistic and unbiased as possible (Horn et al. 2018; Nordbladh 1981).

Fig. 6.2 The large human figure on a panel in Aspeberget (RAÄ Tanum 18:1; L1967:2415) is an example of modern vandalism, but also shows how freshly carved rock art is lighter than the surrounding rock. The strongly white figures are the result of painting in Bronze Age rock art for the purpose of documentation. (Image: Catarina Bertilsson, SHFA (CC-BY NC))

Even though they could not record it, the depth of the petroglyphs was always a crucial feature even for traditional methods, i.e. rubbings and tracings. These methods included several interpretative steps starting from a tactile survey of the rock's surface to feeling differences in the grain structure that would enable the investigator to differentiate between carvings, natural features, erosion, and damage (Milstreu and Prøhl 2020). At best, several documenters are involved, mutually checking their interpretations (Most recently Toreld and Andersson 2015). The result of this investigation is then transferred to the rock using chalk, which is then transcribed to plastic sheets using drawing or stippling techniques. Alternatively, paper is put over the area which is then rubbed with graphite (summarized in Horn et al. 2018; Nordbladh 1981).

Each of these steps includes considerable human bias, because the decision of whether a line is carved or a natural feature relies heavily on experience, expectation, and assumption (Bertilsson et al. 2017; Horn et al. 2018). This bias is directly inscribed into the fabric of the documentation, which means reductive documentation is always already interpretive. This interpretation is then carried over into the investigation of research questions perhaps by other researchers, who may find it difficult to trace this back. The second major disadvantage of traditional methods is their reduction of the three-dimensional heritage into a two-dimensional plane. Although some cues to the depth differences in carved lines can be gleaned from rubbings, and some newer tracings which attempt to indicate superimpositions (for example Toreld and Andersson 2018), this is yet another layer of interpretation because tracings and rubbings both do not depend on real numerical depth values (Horn et al. 2019). Tracings provide an additional major problem since they are an abstracted representation of the surface structure, for example erosion patches are shown in red circles and ice-lines are only shown by a single rough indication of their overall direction. This is problematic, because natural features are sometimes included in the carvings and would then be erased from the documentation

(Fig. 6.3a–b). There are several additional minor problems, but they have been described in detail elsewhere (Bertilsson et al. 2017; Horn et al. 2018). Despite all the criticism, it has to be acknowledged that the reductive methods provide compelling, easy to read, and clear depictions, which is perhaps the reason why they are still preferred in the illustration of research articles.

The 3D recording methods used most in rock art documentation are laser scanning and Structure from Motion (SfM) photogrammetry. Another photogrammetric approach that provides promising results is Reflectance Transformation Imaging (Bertilsson et al. 2014, 2017; Bertilsson 2015; Horn et al. 2018; Horn et al. 2019; Meijer 2016; Meijer and Dodd 2018, 2020). Newer proposed extensions to these methods include using macro- and micro-photography for photogrammetry (Plisson and Zotkina 2015).

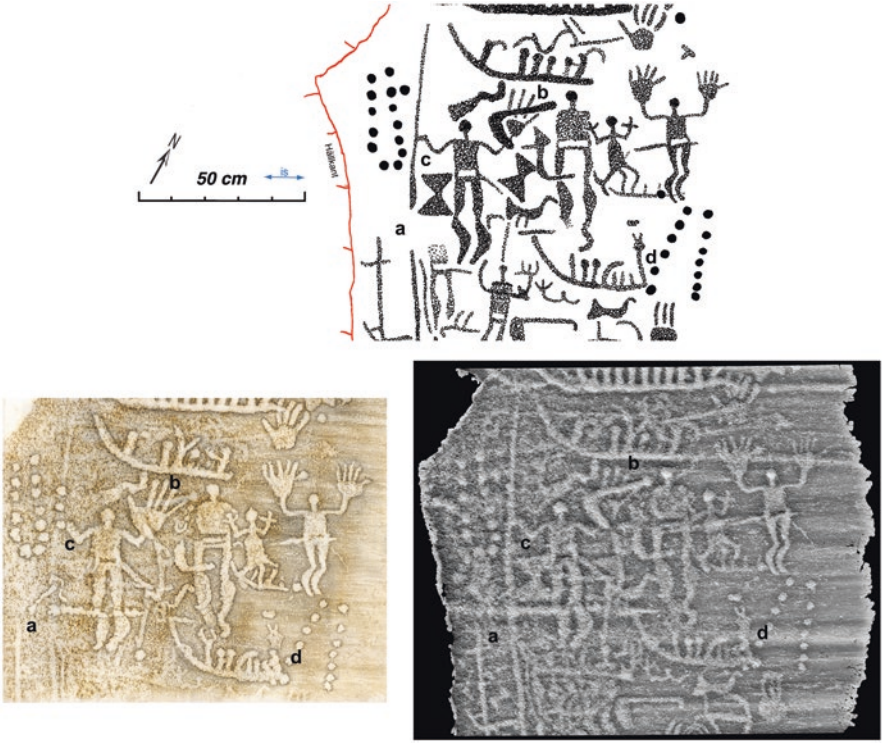

Fig. 6.3 Three documentations of a panel in Brastad (L1970:9162; 142:1) demonstrate the inscribed biases in traditional documentation (top center: tracing by Stiftelsenfördokumentation av. Bohuslänshällristningar, bottom left: rubbing by Dietrich Evers, and bottom right: ratopoviz visualization; laser scan by Henrik Zedig; visualization by Oscar Ivarsson & Christian Horn): (**a**) tracing shows a continuous line as interrupted, but discards the fissure which goes through the line; (**b**) the rubbing focusses on the hand and almost omits the stronger object that superimposes it; (**c**) the rubbing presents the hour-glass figure too weakly and the tracing omits the intersection with the human; (**d**) the tracing omits details of the right prow of the boat and the rubbing deemphasizes the top part of the prow. (All images provided by SHFA)

Reductive and 3D documentation methods have a selection bias, in the sense that a decision is made on what to record. However, baring technical issues in the recording or processing of the data, these methods simply record everything within their scope without additional bias. Thus, eliminating the recording bias of the reductive methods, meaning that the documentation itself is not an interpretation in which bias is inscribed. This allows 3D documentation to postpone the introduction of bias to the final data interpretation step which makes any scientific work more controllable. Furthermore, by its very nature 3D recordings provide a more faithful reproduction of the rock art since it has no dimensional reduction.

6.3 Advantages of 3D Documentation Compared to 2D Recordings

One of the advantages of 3D documentation is the flexibility in its analysis. It can be turned and scaled without any barrier, we can go from a birds-eye view, potentially even looking at multiple sites in their landscapes, to a close-up focussing on a particular image. This close-up can go into the microscopic scale assuming the right equipment like macro- or micro-lenses was used during recording. The freedom to move the viewing angle means that we can analyse several perspectives on the rocks and the images on them, and even compare several perspectives directly. This is important because documentation of rock art is usually a birds-eye overview which obscures how the images interplay with the topography of the surface (Helskog and Høgtun 2004). Multiplying these perspectives in drawings is difficult and time consuming. From a 3D file they can be produced in seconds.

In a recent publication of a reductive documentation of the famous Vitlycke panel (RAÄ Tanum 1:1; L1968:7678), the authors claim to have the advantage of viewing the panel from limitless perspectives and angles when they analyse the panel before and during their documentation (Toreld and Andersson 2018). This, of course, is true to an extent because while on the panel they can stand up, move close, and shift their perspective. With 3D documentation however, the advantage is everyone can do this *after* the recording. After documentation with tactile methods, the documentation is simply flat and fixed to the perspective the documenter has chosen. However, even while in the field, the documenter is more limited than Toreld and Andersson (2018) make out. True bird's eye views, perhaps even with rapidly shifting perspectives, are almost impossible in the field. Close up observations are also limited, since to our knowledge rock art documenters rarely bring lenses to the field, and there is a strong emphasis on using the sense of touch rather than visuals.

In a recent comparison of and criticism on traditional and 3D methods, both, Meijer and Dodd (2018) maintain that rubbings do not demand interpretation. On a theoretical level, this is true. Imagine that we were somehow able to let a machine make a rubbing that exerts equal pressure and consistent graphite application across the entire documented surface. That would be a visualization that is – as Meijer and Dodd (2018) put it – purely surface based. However, in reality, this is rarely the case because documenters have experience and expectations. Known figures tend to be brought into the centre of the paper that is fixed on the rock, because the rubbing tends to be weaker towards the sheet border. This can make figures, especially those that were not known about previously, hard to spot (Figs. 6.3b and 6.4). Some figures show stronger application of graphite than others. The reasons for this may be varied, for example, someone might get excited by a figure showing up strongly, while they are less vigorous in areas where they expect nothing. Willingly or not, this is the inscription of bias into the documentation.

We are sympathetic to the demand of using multiple documentations and documentation methods for rock art research (see Horn et al. 2018; Meijer and Dodd 2018). However, we do not share their darker vision that the digital methods will remove rock art researchers from the original surfaces because it will always be necessary to engage with the original bedrock surface analysing it to find panels which merit documentation through laser scanning or SfM. It is unfeasible to record every single exposed rock art surface on the off chance that there may be something carved. Inevitably, there will be the odd misplaced target point, however, it would be a tall order to maintain that traditional techniques are free from similar human failures. Meijer and Dodd (2018) suggest that there will always be people that take whatever comes out of a computer at face value. However, we do not think that this

Fig. 6.4 Rubbings clearly showing the borders between the different paper sheets (**a**) and a stronger rubbing where images were suspected (**b**). (Rubbings by the Rock Care Project, provided by SHFA)

is a change to the status quo. Secondary users of rock art documentations have mostly assumed that the documentations are for the most part reliable and – outside dedicated rock art research – have rarely criticised or questioned the method or content of any documentation directly. This is precisely the reason why we should strive for bias *reduction* while acknowledging that preventing any bias might be impossible.

The same authors state in a recent publication of 2D and 3D documentations from various sites in Tanum (Sweden) that rubbings are highly accurate, because "*a human hair trapped between the* [rubbing] *paper and the surface is visible on the rubbing*" (Meijer and Dodd 2020). Human vision or in this case visual acuity is a complex issue so only a few comments can be made here. Human acuity is approx. 1 min of arc which means that at the minimum focus distance of ca. 10 cm for a perfectly healthy human, the visibility limit is 0.03 mm (Diniz et al. 2018). Since normal European hair is on average between 0.06 and 0.08 mm in diameter (Jackson et al. 1972), the hair is actually very large and unsurprisingly can be seen from quite a distance away. We are, of course, speaking about theoretical possibilities, and here is where the potential of the 3D documentation methods shines. The CreaformHandyscan 700 currently employed in the work of the Swedish Rock Art Research Archives (SHFA) has an accuracy limit of 0.03: the limit of human naked eye vision. However, on screen, we can move much closer because this is not affected by human focus distance. Of course, rubbings would not pick the hair up, was it in a carved line. For 3D models, this is not an issue and with micro-photogrammetry, we can already go far beyond the capabilities of human vision (Plisson and Zotkina 2015).

6.4 Problems in 3D Documentation

To achieve bias reduction, and to identify development potential for documentation methods, it is important to be transparent about issues related to 3D documentation of rock art. Some of this has already been discussed, for example, that target points can cover up carved areas (Meijer and Dodd 2018). There are other procedural problems, for example, especially with larger panels where there can be gaps in the photo coverage which will only be obvious once the model has been calculated upon returning from fieldwork. Too much light is problematic for the laser scanner, and SfM can struggle with intermittent dark and light patches. Rain or wet surfaces are detrimental to both methods as the surface reflections prevent effective capture.

Bertin (1983) considers in his 'image theory' the capacity of each human eye to only perceive a 2D image. For the perception of three dimensions, human vision requires multiple visual cues (Welchman et al. 2005): Stereoscopic vision, accommodation, parallax, size familiarity, and aerial perspective. In the natural world, this is not an issue as it is three dimensional and provides these cues. To perceive the three dimensions of a model on a screen, either the model has to be moved or light needs to be moved across their surface to provide the necessary cues. In a still image, some of the observations based on the surface shape tend to disappear depending on the lighting angle (Horn et al. 2019).

This becomes especially problematic when we consider that 3D models easily exceed more than one or even several gigabytes in size (Table 6.1). In Scandinavia, this becomes a more pressing issue because full site 3D documentations of larger rock art sites are still underrepresented. Large file sizes can of course be made smaller, but this directly converts into a reduction of the resolution, and therefore, the quality of the model. Such steps need to be undertaken to upload models to public repositories such as Sketchfab which allows institutional users an upload size of only 200 MB. Storage on servers and in clouds is still expensive, so journals usually do not want to host multiple, large models.

For all these reasons it is imperative to develop efficient visualization methods of 3D documentation. The aim is to show the content of the panel in a way that conveys a maximum of information including images, superimpositions, and topography, but also achieves the clear and compelling nature of reductive documentation methods. This should be achieved with as little manipulation of the data as possible to keep the information suitable for scientific inquiries.

6.5 Revealing Rock Art

To tackle the challenge of providing good visualizations that keep as much information as possible, we have developed three different techniques based on roughly similar principles. All the approaches that we developed focussed on curvature, depth maps, and on previous work concerned with this. The open source software Visualization ToolKit (VTK) and Paraview have been used to produce visualizations from the variation of relative and absolute elevation (Trinks et al. 2005). These produced good visualizations revealing especially deeper carvings such as cupmarks and outlined a way forward for other workflows. Another approach called "AsTrend" produces excellent visualizations. However, it uses the LiDAR Visualization Toolbox which causes distortions on slopes (Hesse 2010) and by now it is outdated receiving its last update in 2014. The authors also manipulate the relative values of pixels, for example, through the Adobe Photoshop dodge and burn tools (Carrero-Pazos et al. 2016; Carrero-Pazos et al. 2018) which meant that they cannot be used any longer to estimate depth differences. There are some other approaches which create reasonable visualizations, but that are relatively inflexible (Mark 2017). This is the background for our own efforts to create visualization methods with the aim of providing better clarity, flexibility, and applicability.

From the results of the 3D-Pitoti project, we adapted the idea to work with depth maps generated from the 3D data (Zeppelzauer et al. 2016). Depth maps are 2.5D raster images (GEOTIFF) that store depth values in each pixel represented through a grayscale colour ramp. However, visualizing rock art directly using these is problematic as the rock art is represented by height differences that are more subtle than the extreme values of the natural global curvature. On a different spatial scale, this is surprisingly similar to the problems researchers that use LiDAR data face, because the cultural remains they want to study are often obscured by larger natural height differences (Bennett et al. 2011; Crutchley 2010).

Table 6.1 File size comparison

	Finntorp 89:1	Finntorp 95:1	Finntorp 184:1	Vitlycke 1:1	Hoghem 160:1	Gryt 1:1	Tanum 311:1	Fossum 255:1	Tanum 198:1
Extent (cm)	600 × 500	250 × 120	480 × 400	2240 × 760	880 × 250	830 × 320	900 × 600	1300 × 500	1400 × 500
Sqm.	30	3	19.2	170.24	22	26,6	54	65	70
3D model file size (. obj)	796	602	510		721	1010	1620	2800	3860
LRM output (.tiff)		27.1	32.4		19.3	10.9	19.1	20.5	24.1
LRM output (.png)		20.1	23.3		12.7	5	10.3		16.3
		95.5	93.65		97.32	98.92	98.82	99.27	99.38

Software solutions like ArcGIS include local relief modelling tools (LRM) like Focal Statistics to deal with the issues represented by LiDAR data that have successfully been implemented to visualize rock art as described elsewhere (Horn et al. 2019). Essentially, the global curvature is calculated by blurring the depth map and then subtracting that output from the original depth map. What remains is a depth map of the local depth differences (Fig. 6.5). The result provides the same clarity as good rubbings, but has the additional advantage that the colouration is based on real depth values with a consistent spread. This means that the human bias in colour application to traditional rubbings has been alleviated, and that superimposition and depth differences can be observed in detail. Another advantage is the freedom to adjust the colour ramp and the zoom applied. Apart from 2D outputs, the LRM tools also allow images with a 3D feel by calculating the percentile used in the focal statistics step (Horn et al. 2019). Furthermore, it is possible to produce overview and detail images from the same file.

We also developed an approach that works independently of GIS software by programming an application named “ratopoviz” (rock art topographical visualization). It was specifically set up to accept common laser scan mesh formats to produce several visualizations that were subsequently used for machine learning training. Ratopoviz is an automated pipeline that samples a point cloud from the mesh using the vertices, and then removes outliers through noise detection and a clustering algorithm. The point cloud is then projected into two dimensions using Principal Component Analysis, the pixels are projected into a barycentric coordinate system and the z-values are stored in the pixels. In addition, a normal map is calculated. The global curvature is isolated with Gaussian blurring using a parameter related to the standard deviation (Zeppelzauer et al. 2015) and the removal is guided by further mathematical modelling. Through colour ramp enhancement, both in RGB and B/W using the standard deviation and blending with the normal map, six different outputs are exported as PNG files.

We have also begun developing a method to create low poly models in Agisoft (500 polys) and create relaxed UV maps (2D images representative of the 3D surface) for them in RizomUV. The 3D models are then imported into Substance Painter and processed using the high poly version of the model to bake normal maps and curvature maps. The curvature map is then enhanced using a “levels” node, which is akin to changing the contrast of the image. Additionally, a filter driven by the curvature map fills areas that feature curves. Together these create a lightweight model that highlights the areas of the surface with local differences in height and curvature while ignoring the global curvature of the surface. This allows us to generate maps and visualise entire surfaces at once and enables us to apply different colours to depth differences on a sliding scale. Altogether, with the model and 2 k texture maps the output is often less than 2 MB. These lightweight models ideal for mobile applications visualizing the rock art heritage for visitors.

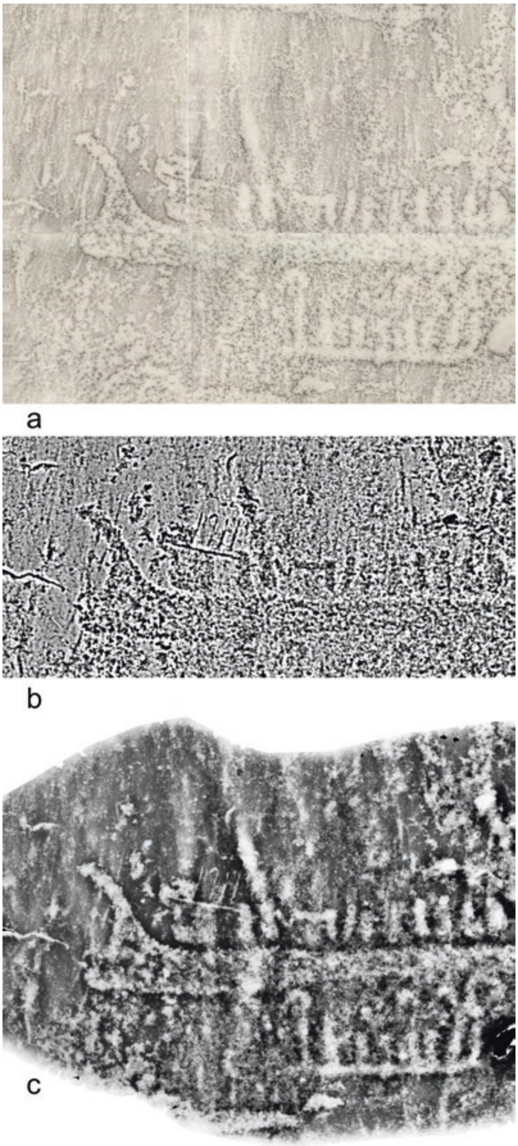

Fig. 6.5 Left part of a boat in Lövåsen: (**a**) rubbing (Tanums Hällristningsmuseum Underslös), (**b**) visualization using local relief modelling (Christian Horn, Rich Potter, and Derek Pitman), and (**c**) ratopoviz (scan by Henrik Zedik, visualization by Oscar Ivarsson and Christian Horn). (Provided by SHFA)

6.6 3D Documentation and Visualization – What Is it Good For?

6.6.1 Preservation

To monitor rock art and help its preservation, it is important to know the exact current state of the carvings. This can be shown on some images in Lövåsen (RAÄ

L1967:2412; Tanum 321:1) which the SHFA documented in the summer of 2020. On the panel there is a boat that contains a partial human figure. The head and the right arm of this figure are partially destroyed by a modern inscription that reads "1911" (Fig. 6.5). It can be assumed that the inscription dates itself. However, in a rubbing produced by Tanums Hällristningsmuseum Underslös (THU) in 2010 this is hardly visible and the number itself cannot be identified. Interestingly, in a laser scan conducted by THU on the same site, the "1911" is clearly visible (Milstreu and Prøhl 2020). Now that we know the modern damage to this rock carving and its precise form, it is possible to monitor the site for further potential and new damage. That such damage is not just a nightmare archaeologists conjure up was demonstrated by the destruction of the famous skier in Tro (Nordland, Norway) (Orange 2016).

6.6.2 Discovery

For research and its dissemination, it is important that the documentation conveys as much information as possible. It is in a sense surprising to find that the rubbing of the boat in Lövåsen published by THU reveals more information about the left terminus of the boat than the published snapshot of their laser scan (Milstreu and Prøhl 2020). In the rubbing, it appears that this part has a carved half oval area that accentuates the prow. This cannot be observed in the scan (Milstreu and Prøhl 2020). This possibly has to do with the light angle chosen for the screenshot illuminating the area in a way that hides this information. A visualization generated with ratopoviz using this scan shows that there are two half ovals next to each other that have only been lightly engraved (Fig. 6.5). Thus, it appears that this boat has two phases and at some point may have looked like a mix between a boat with a hull that was fully carved out and one with uncarved segments separated by carved lines along the hull. The segments were potentially applied after the hull was initially fully carved, but lightly hammered out, because they appear to be deeper.

6.6.3 Outreach

On the same site, it was also possible to observe how deceiving the red paint, which is applied to the carvings to guide tourists in seeing the images, can be. While the impetus is laudable, it is unfortunately often blatantly wrong meaning that tourists are misled. On panel L1967:2632 (Tanum 325:1), a spearman is painted with a short neck and a small head, seemingly stabbing a small boat (Fig. 6.6a). The 3D visualization shows a much more complex figure with a long neck extending above the spear shaft. The head is articulated and shows features that could be a combination of any two of the following: a nose, a neck ring, or a helmet. The figure has hands extending ever so slightly above the spear shaft. The lower legs and feet were either

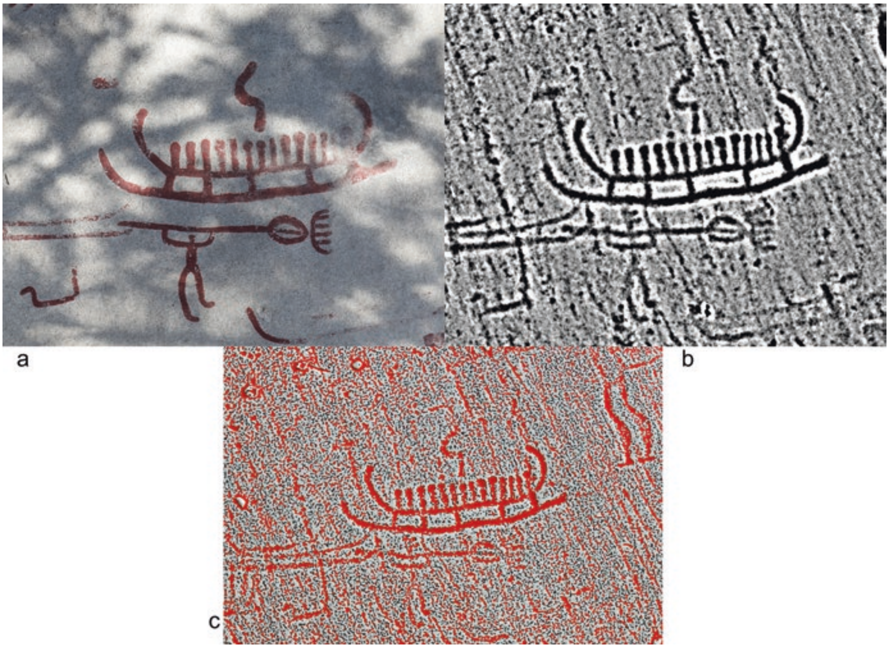

Fig. 6.6 Spearman and boat in Lövåsen: Photo showing how it is presented to tourists in modern red paint (Rich Potter) (**a**), visualization using local relief modelling (Christian Horn, Rich Potter, and Derek Pitman) (**b**), visualisation using the enhanced curvature map (Rich Potter) (**c**)

carved deeper initially to emphasize them, or were applied later. Alternatively, they could have been recarved on several occasions (Hauptman Wahlgren 2004). The supposed boat is in fact more likely an animal as indicated by the outward bend on the top, although it may have an exceptionally long snout (Fig. 6.6b).

Above the figure is a boat and above that a square carving. Here the carvers seem to have used a natural line to indicate what may be the handle of a hammer (Fig. 6.6b). The left keel extension of the boat seems to have been extended somewhat after the initial carving. Above the sickle-like feature is another animal which is slightly damaged in the neck area, but may be rather like the animal in front of the spear (Fig. 6.6b). Lastly, above the right prow, there is a small human figure perhaps carrying a sword (Fig. 6.6b). The keel extension, the animal, and the human were also missed in the rubbing documentation, because while graphite application was done vigorously on the boat to see all the details, the rubbing above the boat was conducted with less pressure or repetition (Fig. 6.6a). This means this area is lighter and the weaker images and details do not show in the final documentation (Milstreu and Prøhl 2020). Here we can see directly how experience and expectation imbue human bias directly into rock art documentation. Such documentations potentially inform the red painting for the tourists and present a skewed image to the public.

6.6.4 Going Back to the Rocks

For preservation, research, and outreach, highly detailed 3D documentation and visualization should be the standard for documenting every rock art image. Long-term storage in an online, open access repository like the SHFA, and in other places for data redundancy, guarantees the availability, viability, and sustainability of this documentation. It also means that funding opportunities for such infrastructures should exist that allow their long-term survival as otherwise this wealth of information will become more difficult to access or vanish completely. However, checks and balances are also imperative. This means 3D documentations need to be checked against documentations made with reductive methods, especially rubbings and, of course, those documenting the rocks should literally not lose touch with the rocks (Meijer and Dodd 2018).

Moreover, an overseen aspect of documentation is geological expertise, which should, if possible, be included in the process of analysing rock art sites. Work on the impact of producing rock art on the rock grain structure and its significance for the interpretation of images and engraving techniques has only recently begun, for example in the project "Tracing carvers on the rocks" (Swedish Research Council). The recent documentation of a small boat at Bro utmark (L1967:2645; Taum 192:1) whose centre is impacted by circular exfoliation indicates that some of the former image may still be preserved in the damaged area (Milstreu and Prøhl 2020). This was confirmed with a 3D recording and visualization of the boat in question. A geological analysis using a magnifying lens and microscopic camera indicated that very faint traces of the carved area were still preserved. Based on this, we were able to suggest an interpretation of how the boat may have looked originally (Fig. 6.7a–b).

6.6.5 Going Forwards

Some years ago, Kristian Kristiansen suggested that archaeology was undergoing a "third science revolution" of which big data was an aspect (Kristiansen 2014). The challenge is to use new methods to address the mass of data that is represented in rock art. Digital archaeology, like the digital humanities, has undergone a computational turn (Berry 2011) and machine learning has been introduced as one method that is gaining momentum. These computational methods can be used to create automatic and semi-automatic approaches to rock art segmentation, image classification, and object localization (Cai 2011; Poier et al. 2016, 2017; Seidl 2016; Zeppelzauer et al. 2015, 2016; Zeppelzauer and Seidl 2015). If such algorithms are trained on larger datasets, then they have an increased likelihood of providing a high-powered statistical tool to sequence rock art images, and discover regional groups of similar images and chronology by employing different lines of evidence. These are quantitative studies, but they are not contradictory to qualitative

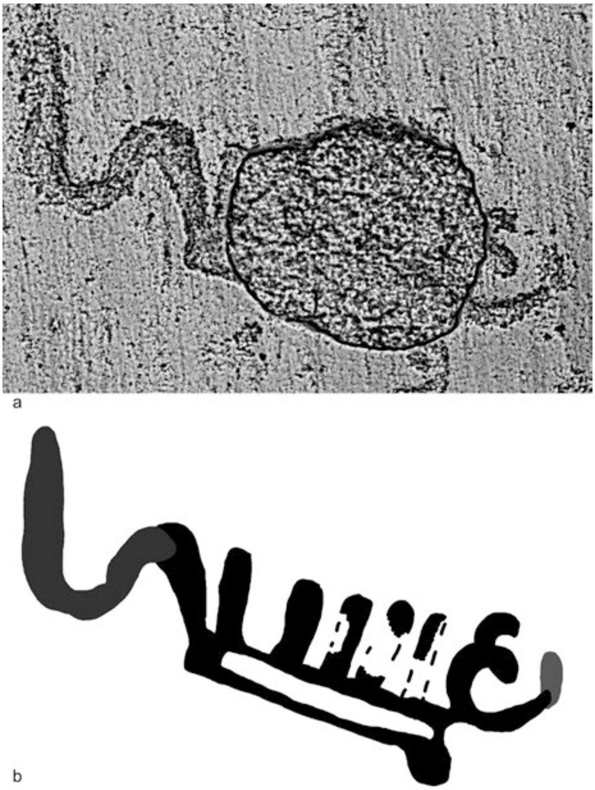

Fig. 6.7 Small boat in Bro utmark: Visualization using local relief modelling (Christian Horn, Rich Potter, and Derek Pitman) (**a**), interpretation based on the field observations, microscopic analysis, the 3D model, and the visualization using local relief modelling (**b**)

approaches, both should be brought into dialogue and can inform each other. This conforms with Ezra Zubrow's (2006) theoretical outline of digital archaeology which emphasizes the very small and the very large, i.e. larger processes and detail observations.

To achieve this, initial training of a Faster R-CNN object detector (Ren et al. 2016) was initiated using the ratopoviz visualizations; this was called RAOD (rock art object detection). The training used a supervised approach with manually drawn bounding box labels on 408 laser scans and employed data augmentation and transfer learning to optimize training with the data available to prevent overfitting on the training data. RAOD identifies and localises rock art within an image and then the detection is assigned a pre-defined class label. The mean average precision (mAP) reached 32.5 for the best performing model. The class boat, with a mAP of 64, outperformed other classes while the class animal only had a mAP of 10 (Table 6.2). Boats are, despite some variation, a group with a relatively concise shape and frequent occurrences. Conversely, animals were a remarkably diverse group, even

Table 6.2 Mean average precision (mAP) for several models with different input data

	No augmentation No transfer learning	With augmentation No transfer learning	With augmentation With transfer learning
Animal	0	4.8	8.8
Boat	4.7	42	58
Circle	0	7.1	31.4
Human	0	10.2	25.3
Wheel	0	0	21.6
mAP	1	12.9	29

	Image type 1 Curvature removal	Image type 2 + Pixel intensity Transformation	Image type 3 + Blending with normal map
Animal	5.6	8.8	7
Boat	40.1	58	51.3
Circle	57.1	31.4	22.2
Human	27.7	25.3	21.5
Wheel	21.6	21.6	15.9
mAP	30.4	29	23.6

	Multi Type 2 (Type 1 + Type 2)	Multi Type 3 (Type 1 + Type 2 + Type 3)
Animal	7.1	10
Boat	64.1	61.3
Circle	40	33.3
Human	28.9	24
Wheel	22.2	18.8
mAP	32.5	29.5

when only four-legged animals, like deer, horses, boars, dogs, etc. were included. Additionally, there were fewer examples of animals than boats available for the training dataset (Fig. 6.8). These metrics indicate that better results can be expected with additional training data and class labels to limit the in-class variation between rock art samples.

These outcomes of RAOD are opportunities for a dialogue to understand why the algorithm made certain decisions and to see how human and machine recognition differed. Maybe unsurprisingly, RAOD struggled with human creativity expressed in hybrid forms (Ahlqvist and Vandkilde 2018) like boats with horse heads or animals that are similar in form to boats, like the previously discussed figure on the panel in Lövåsen (Fig. 6.9a). However, the object detection results have led to new discoveries. On a panel, RAOD identified a human with 96% confidence that was neither discovered by Åke Fredsjö (1981) nor in an inspection prior to starting the training. This led to a re-inspection of the scan and the visualization and a confirmation that this human figure was present (Fig. 6.9b–c). Here, the machine assists in human-led interpretation, highlighting potential regions for rock art within an image.

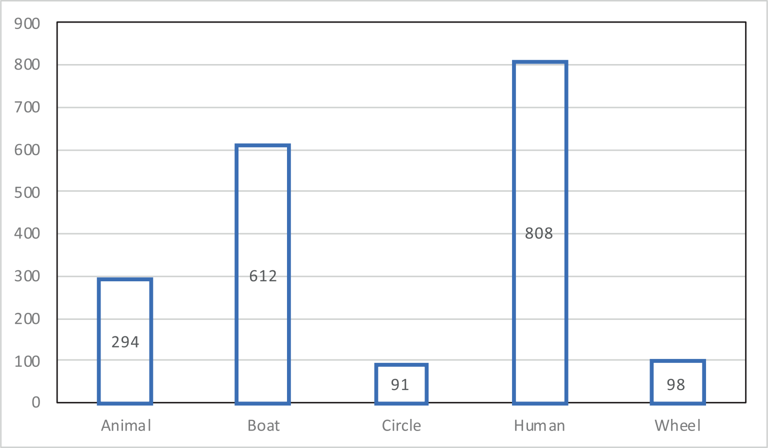

Fig. 6.8 Bar chart of the class labels

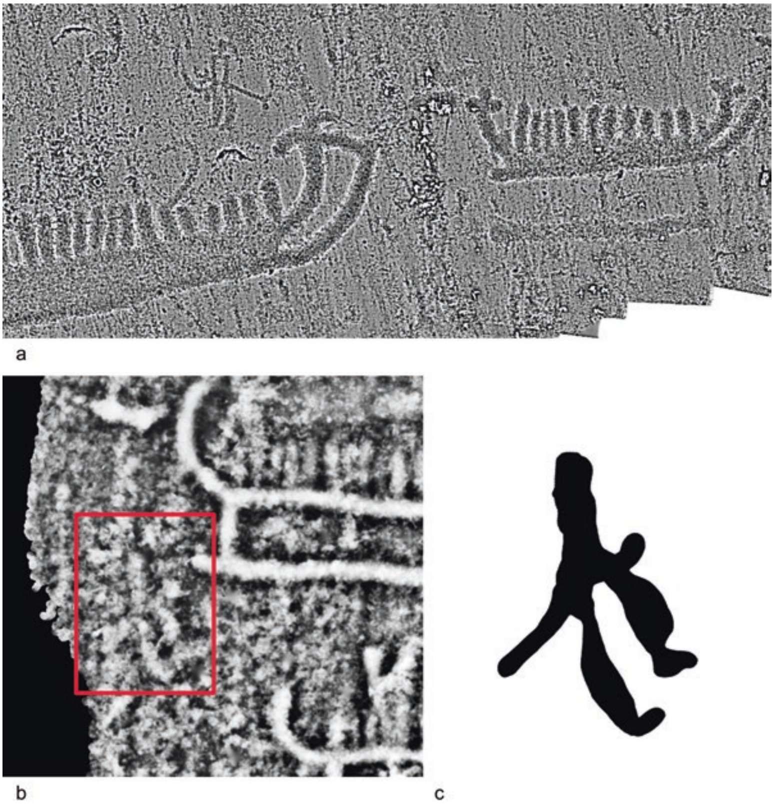

Fig. 6.9 Two boats with animal head prows which the algorithm had difficulties identifying as boats or animals (Christian Horn, Rich Potter, and Derek Pitman) (**a**); ratopoviz output of a detail on a panel in Kville (L1969:5952; 149:1) with a red square indicating the area in which the algorithm identified a human figure with 96% confidence (**b**), and an interpretation of the figure (**c**)

6.7 Conclusion

The power of laser scanning and SfM photogrammetry to record the third dimension of rock art alone should warrant seeing them as the premier method of documenting rock art. As we have shown, 3D data has tremendous potential after its original capture. The potential for visualization at the very least matches the clarity of traditional rubbings, while being even more accurate in spatial relations and depth representation. Furthermore, overview and detail images even going into micro-detail given the right lens can be provided. With that, 3D documentation is an excellent source for the preservation of rock art, research, and outreach, potentially enabling us to discontinue the practice of painting the images onto the rocks soon. Of course, we should not lose touch with the rocks. As has been published earlier (Horn et al. 2018), 3D documentation should not spell the end of reductive methods, especially night photography and rubbings, because they provide important comparative material.

Beginning to train object detection and other algorithms on highly precise 3D data has proven fruitful. In the future, these first results can be used in approaches employing transfer learning and supplying additional traditional documentation data to establish new statistical tools for the research of rock art. As algorithms will undoubtedly become more sophisticated, with more powerful computers, and with more data, the future of rock art research looks bright, with new opportunities and discoveries. It is important to remember that these are tools that deliver outputs which are always in need of interpretation to give them meaning. In that sense 3D, big data, or digital archaeology are theory agnostic and not a contradiction to post-processualism or any other modern theoretical approach.

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References

Ahlqvist L, Vandkilde H (2018) Hybrid beasts of the Nordic Bronze Age. Dan J Archaeol 7:180–194. https://doi.org/10.1080/21662282.2018.1507704

Alexander C, Pinz A, Reinbacher C (2015) Multi-scale 3D rock-art recording. Digit Appl Archaeol Cultural Herit 2:181–195. https://doi.org/10.1016/j.daach.2015.02.003

Bengtsson L (2004) Bilder vidvatten. GOTARC, Serie C, Arkeologiskaskrifter, vol 51. Institutionenförarkeologi, University, Göteborg

Bennett R, Welham K, Hill RA, Ford A (2011) Making the most of airborne remote sensing techniques for archaeological survey and interpretation. In: Cowley D (ed) Remote sensing for archaeological heritage management: proceedings of the 11th EAC heritage management symposium, Reykjavík, Iceland, 25–27 march 2010 / edited by David C. Cowley. EAC, Brussel, pp 99–106

Berry D (2011) The computational turn: thinking about the digital humanities. Cult Mach 12

Bertilsson U (2015) Examples of application of modern digital techniques and methods: structure for motion (SfM) and multi-view stereo (MvS) for three-dimensional documentation of rock carvings in Tanum creating new opportunities for interpretation and dating. In: Troletti F (ed) Prospects for prehistoric Rock Art research: XXVI Valcamonica symposium. Centro camuno di studipreistorici, Capo di Ponte, pp 57–62

Bertilsson U, Bertilsson C, Meijer E (2014) Dokumentation av VärldsarvetsHällristningar med 3D – teknik, Structure from Motion: Etapp 1. PilotstudienpåAspeberget 2014

Bertilsson U, Ling J, Bertilsson C, Potter R, Horn C (2017) The Kivik tomb – Bredarör enters into the digital arena – documented with OLS, SfM and RTI. In: Bergerbrant S, Wessman A (eds) New perspectives on the Bronze Age: proceedings of the 13th Nordic Bronze Age symposium held in Gothenburg 9th to 13th June 2015. Archaeopress, Oxford, pp 289–306

Bertin J (1983) Semiology of graphics: diagrams, networks, maps, 1st edn. ESRI, London: Eurospan [distributor], Redlands, Calif

Cai Y (2011) Pattern discovery from eroded rock art. In: Stanco F, Battiato S, Gallo G (eds) Digital imaging for cultural heritage preservation: analysis, restoration, and reconstruction of ancient artworks. CRC Press, Boca Raton, pp 429–450

Carrero-Pazos M, Vázquez-Martínez A, Vilas-Estévez B (2016) AsTrend: towards a new method for the study of ancient carvings. J Archaeol Sci Rep 9:105–119. https://doi.org/10.1016/j.jasrep.2016.06.044

Carrero-Pazos M, Vilas-Estévez B, Vázquez-Martínez A (2018) Digital imaging techniques for recording and analysing prehistoric rock art panels in Galicia (NW Iberia). Digit Appl Archaeol Cultural Herit 8:35–45. https://doi.org/10.1016/j.daach.2017.11.003

Crutchley S (2010) The light fantastic: airborne LIDAR in archaeological survey. In: Wagner W, Syékely B (eds) 100 years ISPRS advancing remote sensing science: ISPRS technical commission VII symposium. Institute of Photogrammetry and Remote Sensing, Vienna, pp 160–164

Díaz-Guardamino Uribe M, Wheatley DW (2013) Rock art and digital technologies: the application of reflectance transformation imaging (RTI) and 3D laser scanning to the study of late bronze age Iberian stelae. Revista de prehistoria de Andalucía, Menga, pp 187–203

Díaz-Guardamino M, García Sanjuán L, Wheatley DW, Lozano Rodríguez JA, RogerioCandelera MÁ, Krueger M, Krueger M, Hunt Ortiz M, Murillo-Barroso M, Balsera Nieto V (2019) Rethinking Iberian ‘warrior’ stelae: a multidisciplinary investigation of Mirasiviene and its connection to Setefilla (Lora del Río, Seville, Spain). Archaeol Anthropol Sci 11:6111–6140. https://doi.org/10.1007/s12520-019-00909-1

Diniz D, Irochima F, Schor P (2018) Optics of the human eye. In: Yanoff M (ed) Ophthalmology, 5th. Elsevier, Amsterdam, pp 26–38

Foster S, Forsyth K, Buckham S, Jeffrey S (2016) Future thinking on carved stones in Scotland: a research framework. http://www.carvedstones.scot/uploads/4/4/0/3/44032535/cs_scarf_full.pdf

Fredsjö Å (1981) Hällristningar Kvillehärad i Bohuslän, Kville, socken: Del 1 och 2. Göteborgs och Bohusläns fornminnesförening i samarbete med Goteborgs arkeologiska museum, Göteborg

Frieman CJ, Hofmann D (2019) Present pasts in the archaeology of genetics, identity, and migration in Europe: a critical essay. World Archaeol 32:1–18. https://doi.org/10.1080/00438243.2019.1627907

Furholt M (2019) Re-integrating archaeology: a contribution to aDNA studies and the migration discourse on the 3rd Millennium BC in Europe. Proc Prehist Soc 85:115–129. https://doi.org/10.1017/ppr.2019.4

Hauptman Wahlgren K (2004) Switching images on and off: rock carving practices and meaning in Bronze Age life-world. In: Milstreu G, Bengtsson L (eds) Prehistoric pictures as archaeological source: [symposium … at Tanums Hällristningsmuseum in 2002] = Förhistoriska bilder som arkeologisk källa. Tanums Hällristningsmuseum, Tanumshede, pp 149–165

Helskog K, Høgtun E (2004) Recording landscapes in rock carvings and the art of drawing. In: Milstreu G, Bengtsson L (eds) Prehistoric pictures as archaeological source: [symposium … at

Tanums Hällristningsmuseum in 2002] = För historiska bilder som arkeologisk källa. Tanums Hällristningsmuseum, Tanumshede, pp 23–31

Hesse R (2010) LiDAR-derived local relief models: a new tool for archaeological prospection. Archaeol Prospect 79:67–72. https://doi.org/10.1002/arp.374

Höll T, Holler G, Pinz A (2014) A novel high accuracy 3D scanning device for rock-art sites. ISPRS – Int Arch Photogramm Remote Sens Spat Infor Sci XL-5:285–291. https://doi.org/10.5194/isprsarchives-XL-5-285-2014

Horn C, Potter R (2019) A new documentation of "Runohällen" (Gerum, Tanum). Fornvännen 114:129–141

Horn C, Ling J, Bertilsson U, Potter R (2018) By all means necessary: 2.5D and 3D recording of surfaces in the study of southern Scandinavian rock art. Open Archaeol 4:81–96. https://doi.org/10.1515/opar-2018-0005

Horn C, Pitman D, Potter R (2019) An evaluation of the visualisation and interpretive potential of applying GIS data processing techniques to 3D rock art data. J Archaeol Sci Rep 27:101971. https://doi.org/10.1016/j.jasrep.2019.101971

Jackson D, Church RE, Ebling FJ (1972) Hair diameter in female baldness. Br J Dermatol 87:361–367. https://doi.org/10.1111/j.1365-2133.1972.tb07423.x

Kristiansen K (2014) Towards a new paradigm: the third science revolution and its possible consequences in archaeology. Curr Swed Archaeol 22:11–71

Lødøen TK (2015) The method and physical processes behind the making of hunters' rock art in Wetsern Norway: the experimental production of images. In: Stebergløkken H, Berge R, Lindgaard E, VangenStuedal H (eds) Ritual landscapes and borders within rock art research: papers in honour of Professor KalleSognnes. Archaeopress Archaeology, Oxford, pp 67–78

Mark R (2017) Creating a digital rubbing from a 3D model of petroglyphs. Rock Art Res 34:215–217

Meijer E (2016) Structure from motion as documentation technique for Rock Art. Adoranten 2015:66–73

Meijer E, Dodd J (2018) Towards a new era of rock art documentation. In: Dodd J, Meijer E (eds) Giving the past a future: essays in archaeology and rock art studies in honour of Dr. Phil. h.c. Gherhard Milstreu. Archaeopress, Oxford, pp 287–299

Meijer E, Dodd J (2020) The third dimension. In: Milstreu G, Prøhl H (eds) Ryk, Lövåsen, Sotetorp, Bro, Litsleby, Halvordseröd, Trättelanda, Redocumentation. Tanums Hällristningsmuseum Underlös; University of Gothenburg, Tanumshede, pp 63–76

Milstreu G, Prøhl H (eds) (2020) Ryk, Lövåsen, Sotetorp, Bro, Litsleby, Halvordseröd, Trättelanda, Redocumentation. Documentation and registration of rock art in Tanum World Heritage, vol 4. Tanums Hällristningsmuseum Underlös; University of Gothenburg, Tanumshede

Noble G, Brophy K (2011) Big enclosures: the later Neolithic palisaded enclosures of Scotland in their Northwestern European context. Eur J Archaeol 14:60–87. https://doi.org/10.1179/146195711798369346

Nordbladh J (1981) Knowledge and information in swedish petroglyph documentation. In: Moberg C-A (ed) Similar finds? Similar interpretations?: Glastonbury – Gothenburg – Gotland; nine essays. Univeristy of Gothenburg, Gothenburg, pp G1–G79

Oehrl S (2020) Gotland's largest picture stone rediscovered. Fornvännen 115:51–54

Orange R (2016) Norwegian youths who 'ruined' 5,000-year-old rock carving could face prosecution. The Telegraph

Pääbo S, Poinar H, Serre D, Jaenicke-Després V, Hebler J, Rohland N, Kuch M, Krause J, Vigilant L, Hofreiter M (2004) Genetic analyses from ancient DNA. Annu Rev Genet 38:645–679

Plisson H, Zotkina LV (2015) From 2D to 3D at macro- and microscopic scale in rock art studies. Digit Appl Archaeol Cultural Herit 2:102–119. https://doi.org/10.1016/j.daach.2015.06.002

Poier G, Seidl M, Zeppelzauer M, Reinbacher C, Schaich M, Bellandi G, Marretta A, Bischof H (2016) PetroSurf3D: a high-resolution 3D dataset of rock art for surface segmentation. arXiv preprint

Poier G, Seidl M, Zeppelzauer M, Reinbacher C, Schaich M, Bellandi G, Marretta A, Bischof H (2017) The 3D-Pitoti dataset. In: ACM (ed) Proceedings of the 15th international workshop on content-based multimedia indexing. The Association for Computing Machinery, New York, pp 1–7

Ren S, He K, Girshick R, Sun J (2016) Faster R-CNN: towards real-time object detection with region proposal networks. arXiv 1506.01497:1–14

Robinson DA, Williams RBG (eds) (1994) Rock weathering and landform evolution. Wiley, Chichester

Seidl M (2016) Computational analysis of Petroglyphs. PhD, Technische Universität Wien

Sjöberg R (1994) Diagnosis of weathering on rock carving surfaces in northern. In: Robinson DA, Williams RBG (eds) Rock weathering and landform evolution. Wiley, Chichester, pp 223–241

Swantesson JOH (2005) Weathering and erosion of rock carvings in Sweden during the period 1994–2003: micro mapping with laser scanner for assessment of breakdown rates. Karlstad. Toreld A, Andersson T (2015) Ny dokumentation av Kiviksgravenshällbilder. Fornvännen 110:10–26

Toreld A, Andersson T (2015) Ny dokumentation av Kiviksgravens hällbilder. Fornvännen 2015(110):1 s. 10–26

Toreld A, Andersson T (2018) Rock carvings at Vitlycke. Munkreklam, Munkedal

Trinks I, Diaz-Andreu M, Sharpe K (2005) Digital rock art recording: Visualising petroglyphs using 3D laser scanner data. Rock Art Res 22:131–139

Welchman AE, Deubelius A, Conrad V, Bülthoff HH, Kourtzi Z (2005) 3D shape perception from combined depth cues in human visual cortex. Nat Neurosci 8:820–827. https://doi.org/10.1038/nn1461

Zeppelzauer M, Seidl M (2015) Efficient image-space extraction and representation of 3D surface topography. In: 2015 IEEE international conference on image processing (ICIP). IEEE, New York, pp 2845–2849

Zeppelzauer M, Poier G, Seidl M, Reinbacher C, Breiteneder C, Bischof H, Schulter S (2015) Interactive segmentation of rock-art in high-resolution 3D reconstructions. Digit Herit IEEE 2:37–44. https://doi.org/10.1109/DigitalHeritage.2015.7419450

Zeppelzauer M, Poier G, Seidl M, Reinbacher C, Schulter S, Breiteneder C, Bischof H (2016) Interactive 3D segmentation of rock-art by enhanced depth maps and gradient preserving regularization. J Comp Cultural Herit 9:1–30. https://doi.org/10.1145/2950062

Zubrow EBW (2006) Digital archaeology: a historical context. In: Daly PT, Evans TL (eds) Digital archaeology: bridging method and theory. Routledge, London, pp 8–27

Chapter 7
Cross-Modal Search and Exploration of Greek Painted Pottery

Elisabeth Trinkl, Stephan Karl, Stefan Lengauer, Reinhold Preiner, and Tobias Schreck

Abstract This paper focuses on digitally-supported research methods for an important group of cultural heritage objects, the Greek pottery, especially with figured decoration. The design, development and application of new digital methods for searching, comparing, and visually exploring these vases need an interdisciplinary approach to effectively analyse the various features of the vases, like shape, decoration, and manufacturing techniques, and relationships between the vases. We motivate the need and opportunities by a multimodal representation of the objects, including 3D shape, material, and painting. We then illustrate a range of innovative methods for these representations, including quantified surface and capacity comparison, material analysis, image flattening from 3D objects, retrieval and comparison of shapes and paintings, and multidimensional data visualization. We also discuss challenges and future work in this area.

Keywords Greek pottery · Surface mapping · Visual exploration · Shape analysis · Retrieval · Linked Views

7.1 Introduction

3D technology is widely used in different fields of archaeological research (Lieberwirth and Herzog 2016), as means for the documentation of archaeological excavations or historical buildings and even more for recording entire landscapes by

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remote sensing. One field, the documentation of artefacts in concert with computer-aided data analysis, seems the least pronounced one in this popularisation of 3D archaeology. We will focus in this paper on this specific field, more precisely, we will describe 3D technology and search and exploration methods applied in ancient pottery research.

Ancient pottery, so-called “vases” in archaeological terms (Boardman 2001), belong to one of the largest categories of physical remains of ancient cultures, due to the relative durability of its material. Since the eighteenth century, special attention has been given to this category, especially to Greek painted pottery (Flashar 2000), not only as objects of archaeological research but also as a collector’s item (Nørskov 2002). In archaeology, the artistic analysis of the vase painting was often the focal point until late in the twentieth century by neglecting the three-dimensionality of the object. Today, the research questions focus more on the relation between shape and figured depiction, on the iconographic changes during times, on the content and context of the vases, and many more. Overall, the research on Greek vases became a part of the emancipating Material Culture Studies which focuses on the relations between human and object (Langner 2020).

Regardless of the kind of the research questions, an intensive investigation of the vase should be the starting point for each further discussion. This should be undertaken at the best by autopsy, but to explore each single vase relevant for the respective study at first hand is almost impossible due to the world-wide distribution of this material. Hence, an appropriate publication should deal comprehensively with the vase which includes a full range of measurements, detailed photos, unwrapping where necessary, and an extensive verbal description. Scientific analyses could be added to answer some specific questions, e.g., to get information of the provenance by analysing the used potter’s clay, to identify organic markers relating to potential content, to characterise older restorations or even to date the ceramic material.

In the archaeological domain, pottery is usually published in printed media which force the three-dimensionality of the object into a two-dimensional figure. The standard reference for Greek pottery is the *Corpus Vasorum Antiquorum* (CVA), an international research project for the documentation and publication of ancient ceramic from museums, universities and other collections. Since the first volume of the CVA in 1922 more than 400 fascicles have appeared, with more than 100,000 vases. Next to the CVA stands the Beazley Archive Pottery Database (BAPD), a freely available online database of mostly Greek vases (c. 120,000) which allows simple searches and filtering (Mannack et al. 2024). The CVA as well as the BADP are still growing.

This historically developed practice of pottery publications is well-established, but cannot do justice to all the research questions on pottery. With the advent of new digital technologies, contactless 3D measurements using optical scanners and X-ray imaging procedures as Computed tomography (CT) were introduced to establish 3D models of vases with the basic aim to create a more objective and complete documentation. On a large scale, 3D technology was applied for the first time for the CVA Vienna Kunsthistorisches Museum 5 (Trinkl

2011; laser scanner) and for the CVA Amsterdam Allard Pierson Museum 4 (Van de Put 2006, medical CT). Despite constraints at that time of early 3D technology (e.g., the low resolution of acquired texture data towards conventional photography), these innovative approaches have played a seminal role in this field of digitisation of Greek pottery.

Only in the last decade 3D technologies are capable of creating 3D models of pottery objects with appropriate accuracy in geometry and resolution in texture, thus being of equal value to traditional pottery documentation, e.g., by means of photography or drawings. This advance has paved the way to exhaust more comprehensively the potential of 3D models, not only for documentation purposes but also for 3D data analysis, and to develop new methods for searching, comparing, and visually exploring 3D cultural heritage (CH) objects (see the overview in Karl et al. 2022). However, for comparative studies high-resolution 3D models of Greek vases are still rarely available. Therefore, a general aim in this digitisation process of CH objects is to make this data, including all necessary metadata, photos and 3D data, freely available, as it was done by the Online Database for research on the development of pottery shapes and capacities (ODEEG; Lang-Auinger et al. 2021). Additionally, due to the previous publication work on pottery with an extensive quantity of data (mostly photos and drawings), novel ways are needed for a joint exploration of these different modalities.

7.2 Methods of 3D Data Acquisition of Small-Scale Objects – An Overview

The starting point for any kind of digital analysis is the digitisation of the object. Whatever method used, the physical object should be cleaned thoroughly at the beginning. If possible, modern additions, like complemented parts or overpainting, should be removed and further conservation treatment (Kästner and Saunders 2016) should be limited to a minimum.

3D data acquisition methods are based either on direct measurements (e.g., via a laser beam or by triangulation using structured light), on photogrammetry or on X-ray volume reconstruction technology. For the documentation of Greek vases, laser scanning (Hess 2017) was used in the beginning. With advancing technology Structured Light Scanning (SLS) is currently widely used in pottery studies (Rieke-Zapp and Royo 2017). Both techniques are optical methods and ensure the acquisition of precise and accurate geometric data of the ceramic surface. Within the last decades, Computed Tomography (CT) has been developed to be a notable imaging method in the field of non-destructive testing (NDT), enabling dimensional measurements and material characterisation (Carmignato et al. 2018). All these methods result in a well-built 3D model, but lack an appropriate recording of the mostly painted vessel's surface (the texture) aligned to the needs in archaeological research. For acquiring high-resolution photo-realistic surface models which are especially needed for the vase painting multi-image 3D reconstruction like Structure from Motion (SfM) and Dense Multi-View 3D Reconstruction (DMVR) (Koutsoudis et al. 2013; Hess and Green 2017) is currently the most effective solution. The combination of acquisition methods using the strengths in each case has been proven to be leading to the best results (cf. Sect. 7.3.4). A general overview for all kinds of scanning methods, including also the potential and limitations is given by Dey (2018).

All of these techniques share the same overall concept of contactless measuring (no physical touching of the surface) which guarantees an optimised data output by minimising the risks of damage or even (partly) loss of the archaeological substance.

7.3 Applications in Pottery Research – Case Studies

In the following, we will present selected case studies in the field of computer-aided Greek pottery research conducted by the authors and collaborators associated with the CVA community. They are based on diversely acquired digital data and develop novel approaches for further academic discussions.

7.3.1 Unwrappings of Painted Curved Surfaces

A fundamental task of high significance in research on ancient vase painting is the unwrapping of the painted vase surfaces (Walter 2008). These unwrappings show the depictions with minimal photographic distortions or sectioning by separate photos, enabling archaeologists to analyse and interpret the image as a whole in terms of style, dating and iconography. They are typically created manually using tracing paper, which is time-consuming, error-prone, and often not even allowed due to the required contact with the fragile surfaces. Another method, peripheral or rollout photography, is contactless but can only be applied reasonably for cylindrical painted surfaces (Villard 1965; Felicísimo 2011).

Today, various 3D mesh processing and visualisation tools, like the GigaMesh Software Framework (Mara et al. 2021) or CloudCompare (Girardeau-Montaut et al. 2021), allow to perform such unwrappings directly on a virtual 3D model of a vessel (Rieck et al. 2013; Karl et al. 2019). They utilise proxy geometries that exhibit a simple surface of revolution (cylinder, cone, sphere) that best approximates the vessel shape. This proxy is computationally fit to the 3D mesh, which is then unwrapped according to the unrolling of the proxy around its axis of revolution. The resulting rollout can then be projected to 2D, for instance, along an overall optimally orthogonal angle. This results in a "flat" representation displaying the entirety of the vessel surface, but can show considerable distortions in stronger curved surface parts (Fig. 7.1).

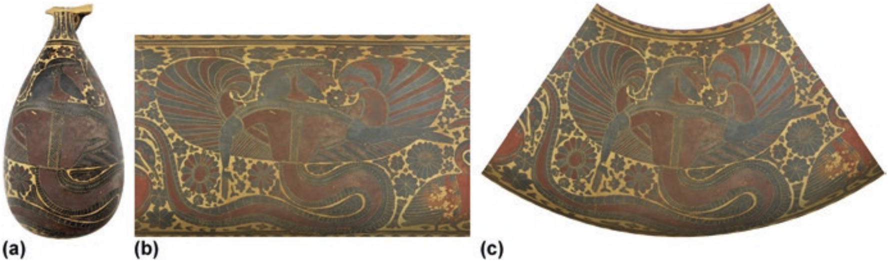

Fig. 7.1 Computer-aided rollouts of the Corinthian alabastron University Graz G28: (**a**) photo; (**b**) cylindrical; (**c**) conical rollout. (© P. Bayer, S. Karl, J. Kraschitzer, University of Graz)

A major issue with these kinds of unwrappings is that unless dealing with purely developable surfaces, the projection to 2D will necessarily introduce different types of surface distortions. Conformal methods strive for preserving angles, that is, avoiding shearing of surface motifs, but can introduce strong undesirable distortions of distances and scale (cf. mapping of the earth: Snyder 1993). In contrast, distance preserving methods introduce strong angular distortions that can render the result useless as well. Especially for pottery objects that exhibit highly curved, bulky shapes, the effects of this mapping problem can become practically problematic in the attempt of creating an all-encompassing depiction of the surface paintings that is true to scale in all relevant details.

To address this problem, more elaborate mapping techniques can be employed that minimise a defined distortion error measure (Floater and Hormann 2005; Sheffer et al. 2006), e.g., using a numeric optimisation on an initial mapping. Starting from a naive unrolled surface with potentially strong distortions (Fig. 7.2b), the Elastic Flattening (EF) approach (Preiner et al. 2018) computes a physics-inspired relaxation of the stresses induced by these distortions on the edges of the 3D mesh. In this process, mesh vertices are iteratively relocated to minimize the deviation of the length of each edge in the planar map from its original length in the 3D mesh. This way, the introduced distortion error is distributed evenly over the surface. As seen in Fig. 7.2c, the resulting depiction is able to significantly reduce both proportional and angular distortions compared to the naive initial rollout. It has also been shown that the EF results widely agree with the layout resulting from manual unwrappings of comparable vases (Fig. 7.3).

This work on optimal digital unwrappings of Greek pottery raises the potential for further research. In contrast to naive unwrappings that produce divisive cuts through different motif parts (e.g., neck of the bird in Fig. 7.3a), future improvements will involve finding optimised layouts that preserve the integrity of the motifs, which is of primary importance for the archaeological interpretation.

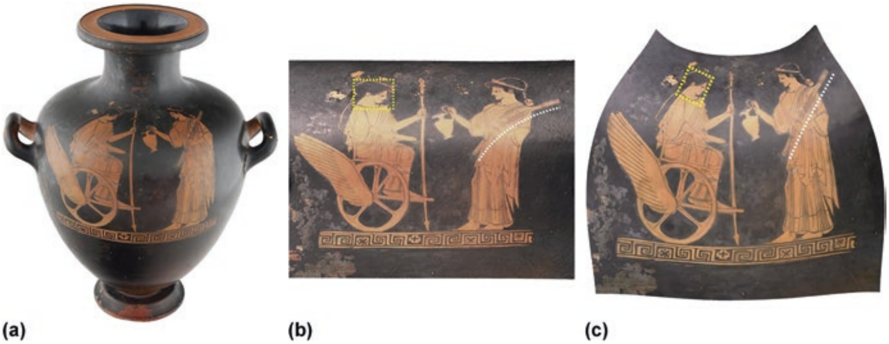

Fig. 7.2 Attic red-figure hydria, University Graz G 30; (**a**) photo; (**b**) spherical rollout exhibiting proportional (yellow) and angular distortions (white); (**c**) Elastic Flattening. (© Preiner et al. 2018, The Eurographics Association)

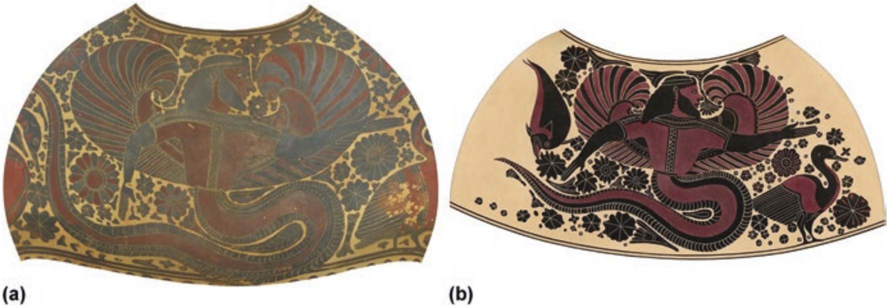

Fig. 7.3 (**a**) Elastic flattening of the Corinthian alabastron University Graz G 28 in comparison to (**b**) a hand-drawn unwrapping of the alabastron Brussels R 224 with comparable motiv from the same vase painter (Lenormant and de Witte 1858, pl. 31). (© R. Preiner, TU Graz)

7.3.2 Shape Comparison

The spatial expansion, the geometry, is among the most significant features of a vase. Shape was always used as classification criteria for establishing typologies. Hence, digital geometric analysis started early, cf. the overview by Pintus et al. (2016), mainly focusing on sculpture (Lu et al. 2013; Frischer 2014) and terracotta (de Beenhouwer 2008).

Whereas the vast majority of the Attic pottery is thrown on the potter's wheel, there is a production of mould-made Attic vessels from the late sixth and fifth century BC, preferably in the shape of a human head, so-called head vases. Replicas of the same mould can be identified by using 3D models and computer aided matching (Trinkl and Rieke-Zapp 2018). The difference between similar head vases can be quantified. It enables the detection of a series that is taken from a single mould (Trinkl et al. 2018). Furthermore, by comparing similar head vases with different heights, at least three interdependent series are evident (Fig. 7.4). This can be explained by the

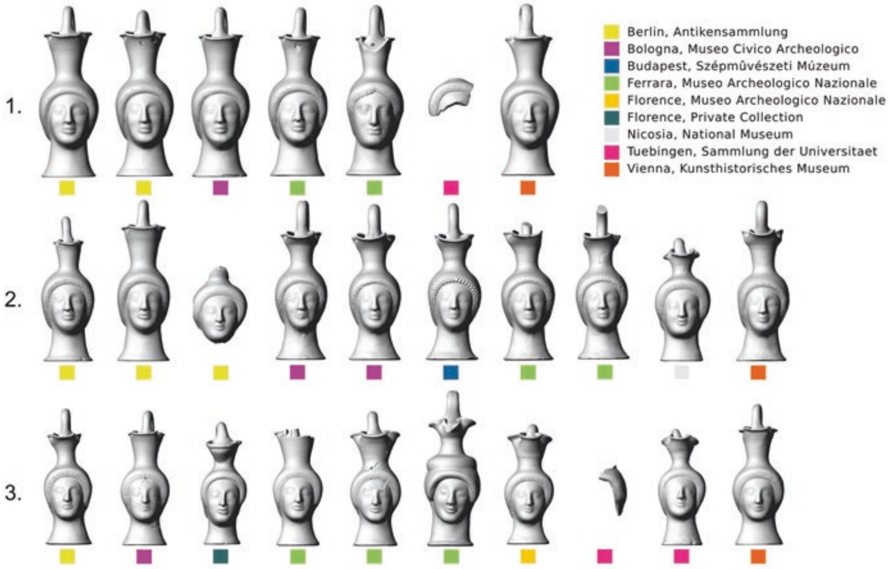

Fig. 7.4 Three interdependent series of head vases stored in nine different collections. (© P. Bayer, E. Trinkl, University of Graz)

manufacturing process of re-molding, which results in copies of progressively smaller height due to the shrinking of the clay during the drying and burning process. The use of digital 3D models also enables the evaluation of fragmented objects, which is hardly possible by an analysis using conventional measurements.

7.3.3 *Filling Volume Calculation*

The shape of a vase and its filling volume are closely related. The determination of the filling volume is essential to detect standardisation in the potters' production and to recognise ancient units of capacity which varied according to location and epoch (Büsing 1982).

If a vase is unbroken and well preserved, the capacity can be measured indirectly by filling the vase with dry granular substances, like rice or sand, and then measuring the capacity of these decanted substances. However, as in practice most vases are too fragile, a contactless measurement has to be performed. For so-called "open vessels", i.e., vases whose inner surface is visible and can therefore be measured, the easiest way is to rotate the measured inner profile and calculate the volume of the resulting body of rotation (Moreno et al. 2018). A web application developed at the University of Brussels provides this computation for domain users (Engels et al. 2013; Tsingarida et al. 2021). Whereas this calculation is based on assuming the volume to be a body of rotation, only 3D scanning can completely capture the inner surface of open vessels and allow an accurate calculation of the filling volume.

With 3D models it is also possible to estimate the inner surface of so-called “closed vessels” (e.g., Fig. 7.5a), i.e., vases of which the inner surface cannot be measured, e.g., because of a narrow mouth. Based on prior knowledge of the wall thickness, an offset of the outer surface towards the interior can be determined to estimate the filling volume (Mara and Portl 2013).

A more complex method for estimating the filling volume of closed vessels is again based on the scanned outer surface, but utilises the mass of the vessel and the bulk density of the ceramic material to calculate the ceramic volume and thus the wall thickness (Spelitz et al. 2020). The material density can be determined from a pottery fragment with the same material properties, so-called “fabric”. Unfortunately, the majority of the vases in museums are restored and completed with other materials, which affects their mass. In general, the determination of bulk densities as characteristic properties for specific fabrics (e.g., Attic or Corinthian) is still at the beginning and requires more large-scale test series (Karl et al. 2013).

The most precise method of receiving the filling volume of closed vessels is to use the 3D data acquired by Computed Tomography (Fig. 7.5d), which, however, requires expensive stationary hardware and is thus less accessible to most domain users.

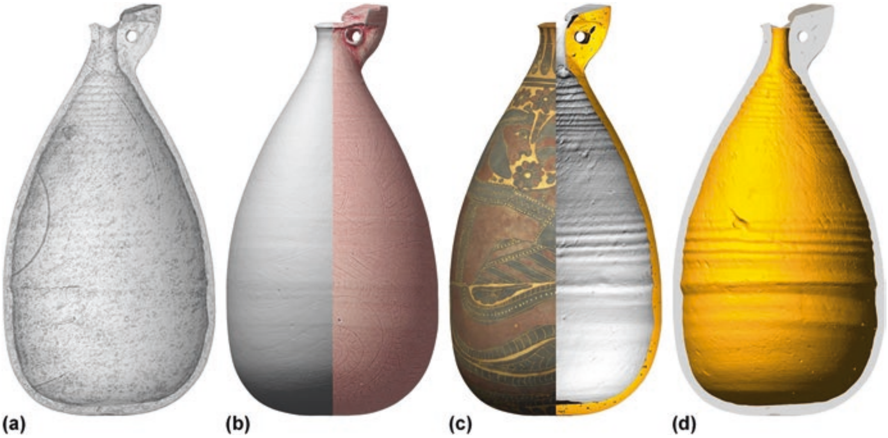

Fig. 7.5 Corinthian alabastron, University Graz G 28: (**a**) Isosurface volume rendering of CT data (transparent modus); (**b**) CT surface with incisions, one half enhanced by using Multi Scale Integral Invariant filtering; (**c**) textured CT surface with sectioning; (**d**) volumetric “phantom” body of the capacity (1,493 ml). (© S. Karl, University of Graz)

7.3.4 Identification of Manufacturing Techniques

Besides shape (geometry) and decoration (texture), manufacturing techniques provide other attributes to classify and interpret pottery; hereby focusing on the choices and changes in technical practices (Rice 2015). In wheel-thrown pottery, which most Greek pottery belongs to, traces of primary manufacturing techniques such as potter's finger striation marks or the location of joints of separated formed parts are mostly preserved in the interior of closed vessels or on subordinate parts. On the exterior, these traces are usually eliminated by secondary smoothing and burnishing, finally by painting.

For this field of pottery analysis, X-ray imaging methods, recently CT were used (Van de Put 1996; Kozatsas et al. 2018). A particular strength of this method is that visualisation and analysis can be performed on the whole vase (Karl et al. 2013, 2014). CT provides an accurate and complete 3D documentation of an object encompassing all internal structures (Fig. 7.5a); even fine details such as the incisions of the black-figure style can be displayed due to the high resolution (Fig. 7.5b). The CT model can be additionally combined with texture information, e.g., acquired from an SfM model (Fig. 7.5c). Based on the recording of the object's interior surface, the vessel's capacity can be calculated with high accuracy (Fig. 7.5d).

While the use of the potter's wheel can be clearly identified by the elongation of voids and other inclusions in a spiral pattern (Fig. 7.5a), separately attached vessel parts are mostly recognised by the change in the structure within the ceramic body. Furthermore, the CT data allows to reveal traces of used pottery tools, ancient repairs during the manufacturing process (Karl et al. 2018) or modern interventions and additions.

A unique point of CT compared to all other methods is the fact that it is able to "look" into the material without cutting it (Fig. 7.6). Depending on the accuracy of the CT scan, it enables a detection and morphological analysis of the air pores (voids) and inclusions within the ceramic matrix (e.g., according to amount, size, shape). Matrix is commonly termed the fine micaceous basic substance of the burnt clay, while inclusions are so-called non-plastic components, mostly originating

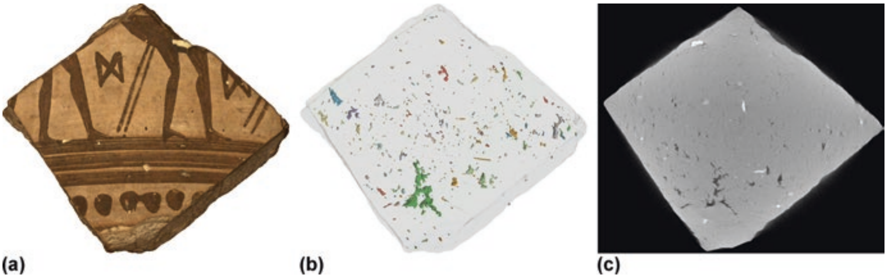

Fig. 7.6 Fragment of an Attic Late-Geometric krater, University Graz G 517: (**a**) 3D model; (**b**) 3D visualisation of porosity (connected voids colored), (**c**) CT cross-section with voids (black) and different inclusions (middle grey and white). (© S. Karl, K.S. Kazimierski, University of Graz)

from tempering the potter's clay. The fact that these inclusions become visible at all is due to the complex assemblage of the ceramic material, which consists of mineral particles of different specific gravity, e.g., clay minerals, quartz, feldspars or iron oxides. A quantification of the clay fabric properties enabled by this non-destructive method allows for a material characterisation, which is an important methodology in pottery research (Gassner 2003), not only for questions of manufacturing technology but also for the localisation of the production site or the workshop.

Even though CT offers a high potential in documentation and identification of manufacturing techniques, it comes with certain drawbacks. First, the sensitive objects must be transported from its storage location to a specific CT lab, which often requires additional efforts and precautions. Moreover, typical CT artefacts like beam-hardening can affect quantitative analyses and CT surface reconstructions (Carmignato et al. 2018; Kazimierski and Karl 2015). Future research in the archaeological domain will have to consider the use of mobile and more flexible X-ray imaging devices for achieving adequate information of the vessel's interior.

7.3.5 Shape-Based Retrieval

Apart from individual analysis and pairwise comparison, an essential task in pottery research involves the comparison of multiple objects to a query in relation to different similarity traits, e.g., shape, texture, painting style or metadata. Retrieval methods enable to rank the objects in a (possibly huge) database with regard to a given query, which generally consists of keywords, but can also comprise images, sketches, or 3D shape information (Biasotti et al. 2019; Rostami et al. 2018).

In terms of Greek pottery the objects' shapes are a fundamental trait for comparison. To date, many shape analysis methods have been proposed for applications in CH object data (Pintus et al. 2016; cf. 3.2). The amount of published vases is huge and accompanied with comprehensive metadata and a high number of images, while 3D models are rarely available. Hence, one has to resort to comparing their shapes based on available images depicting their silhouettes, using appropriate image comparison techniques.

These images are compared using mathematical representations of characteristic features of the silhouette, image color patterns, etc. These so-called "feature descriptors" enable the computation of similarity measures between images. The variety of feature descriptors is vast and they can be divided into engineered features, based on explicitly defined transformations of the input images, and learned features which are relying on machine learning algorithms.

Suitable similarity measures have been obtained e.g., by the engineered Histogram of Oriented Gradients (HOG) (Dalal and Triggs 2005) feature descriptor, which encodes the orientation and magnitude of the color gradients over pixel blocks. An alternative is given by the Shape Contour Descriptor (SCD) (Attalla and Siy 2005) which is solely based on the silhouette of a depicted object.

Fig. 7.7 Shape based retrieval with HOG (**b**) and SCD (**c**) descriptors compared to a manual expert ranking (**a**). Each row shows the ranked top 20 results for a fragmented sample query on a diverse database with 3,340 object depictions. (© S. Lengauer, TU Graz)

State-of-the-art methods also allow to search for similar vases given only fragmented or incomplete vases, by sketching the supposed completed silhouette in a graphical user interface (Lengauer et al. 2020). As shown in Fig. 7.7, these methods provide a high success rate even in case of fragmented query objects.

7.3.6 *Motif-Based Retrieval*

Apart from shape, the ornaments and figural depictions, the motifs, on the painted vases are often an important basis for the analysis and exploration of ancient Greek pottery. These motifs are manifold and include single figures as well as multi-figured scenes (Fig. 7.8a), e.g., deities, mythological figures, weddings, sacrifices or warrior departures.

From a technical perspective, the challenge of finding vases with similar motifs can be split into two major parts: (1) An image segmentation part for composing a database of motifs and (2) a matching part determining the similarity of all motifs in the database to a provided query (Lengauer et al. 2019). Image segmentation describes the process of assigning the pixels of an image to a finite number of coherent regions. For the task of extracting motifs from a picture, those regions should ideally correspond to the individual motif outlines. We have obtained good results in our work with the Efficient Graph-Based Image Segmentation (EGBIS) algorithm (Felzenszwalb and Huttenlocher 2004; Fig. 7.8b) as well as with segmentations based on morphological transformations (Fig. 7.8c).

In the study of vase painting, it is generally accepted that similar motifs have comparable outlines or contours. A feature descriptor like Shape Context (Belongie et al. 2002) represents an appropriate choice for quantifying the similarity of outlines extracted by segmentation to a given query. As shown in Fig. 7.9, this approach allows to find and discriminate similar motifs.

Fig. 7.8 Segmentation examples for a set of images of painted vases (**a**) with EGBIS (**b**) and morphological segmentation (**c**). (© Lengauer et al. 2019, The Eurographics Association)

Fig. 7.9 Motif retrieval examples of (**a**) a standing figure with outstretched arm and (**b**) a winged flying figure, the Eros, with the sorted top results for these different user-defined queries. (© Lengauer et al. 2019, The Eurographics Association)

We find that a successful segmentation for this motif-based approach is often hindered by the degeneration and incompleteness of the vase surface (e.g., in case of erosion) and by the interlinking and overlapping of motifs.

7.3.7 Multivariate Structuring of Large Object Collections

A central task in archaeology is the classification of objects according to various object properties (Adams and Adams 2008). While individual objects are typically classified via similarities to known objects, large collections of (digitised) objects represent a much more tedious task for classification, which typically starts with organising the objects according to their numerous properties (e.g., date, findspot, shape, etc.) and goes further to building groups with common properties. Important insights are mainly based on analysing the relations between these groups, e.g., temporal clusters that are related to object accumulations in a particular site. However, revealing these relations by manual investigation is a highly complex task.

Appropriately designed computer-aided visual analytics tools can greatly support archaeologists in organising and grouping objects with respect to date, findspot, and shape, and allow to visualise significant relations between groups within these

Fig. 7.10 LVVES, visualising a selection of objects structured by findspot (GMV), shape similarity (SSV), and date (TV). Intra-view connections (blue rectangle) are revealed through linking and highlighting mechanisms. (© S. Lengauer, TU Graz)

different dimensions. Different properties can be assigned to different spatial dimensions in an interactive three-dimensional system (Windhager et al. 2020). Network visualisations are an established base technique to illustrate object relations (Van der Maaten et al. 2007; Bogacz et al. 2018) and can also be combined with additional visual metaphors for particular properties, e.g., displaying time as a temporal landscape (Preiner et al. 2020).

An integrated linked view system such as the Linked Views Visual Exploration System (LVVES) depicted in Fig. 7.10, allows the coherent exploration of findspot, date and shape information. This is facilitated through a separate viewer for each of the mentioned properties (Fig. 7.10), consisting of a map for the findspot, a timeline for the date and a network visualisation for the shape information. While the structuring of objects within each view allows for an exploration within a single dimension, an additional intra-view linking mechanism allows to highlight objects in all other views, revealing relations between groups across dimensions (red connections in Fig. 7.10). This approach is not limited to these three properties but can be extended to display additional characteristics like painting style, fabric, and more.

7.4 Discussion and Outlook

Once generated, the benefit of a 3D model is wide-ranging. The digital model may be used, re-used and modified as many times as wanted, without touching the original object again. Using non-tactile acquisition techniques, the protection of fragile objects or objects of poor preservation is provided in the best possible way. A digital documentation can enrich the conventional measuring and description; extend visual capabilities (cf. Sect. 7.3.1), supports quantified surface comparison (cf. Sect. 7.3.2) and enables calculation of capacities (cf. Sect. 7.3.3). Depending on the used methods and tools it even offers insight into the material properties (cf. Sect. 7.3.4).

In particular, the presented case studies demonstrate that vases stored in diverse locations can be compared easily without being moved (cf. Sect. 7.3.2); moreover, partly preserved vases can be included in the evaluation. A digital environment simplifies comparisons of single features of the vase, like shape or motif (cf. Sects. 7.3.5 and 7.3.6), and the linking of features like chronology, findspot and shape (cf. Sect. 7.3.7). By this means new relations can be revealed and already known relations can be visualised.

Additionally, to the above presented analyses of object's properties like geometry and texture, further scientific approaches associated with 3D data can reveal object's properties that cannot be detected by traditional archaeological practice. A very valuable method is the combination with non-visible light (UV, IR) for the detection of conservation details and recent manipulation (Kästner and Saunders 2016; Nocerino et al. 2018).

Conveying the manifold information and complex meaning of Greek vases to non-archaeologists can be difficult. Hence, a 3D model may be applied in the dissemination of expert knowledge to make our common CH more familiar to a growing audience (Quattrini et al. 2020). For various kinds of dissemination, a replica based on a 3D model can be useful, e.g., in exhibitions and in classrooms on various levels of education (Breuckmann et al. 2013).

7.4.1 Challenges

Despite the various prospects of digitisation for the analysis and documentation of vases showcased above, their usage and utilisation for practical archaeological tasks faces several challenges.

The acquisition of the data oftentimes requires special hardware and associated skills for their operation. Moreover, certain digitisation equipment can be rather expensive, others are rarely available and often not mobile. These factors have to be considered when discussing the documentation costs. Furthermore, a future utilisation of the data in new or upcoming archaeological research questions requires defining the detail, quality and nature of the data already at the time of acquisition, which is difficult to anticipate. Approaches for mass digitisation which can be configured for different acquisition modalities, may provide a scalable digitisation infrastructure (Santos et al. 2014).

The preservation of the data itself often comes with considerable long-term storage costs, and has to handle the choice of suitable and accessible data formats and resolutions. Moreover, it is essential to augment the data with suitable meta information that document the nature and parameters of the acquisition process, to ensure their traceability and interpretability.

Once stored, the retrieval of the data, i.e., its computer-aided search and analysis, requires a scalable and well-structured data pool. 3D data, especially from Greek vases, is rarely available in a structured format, and often lacks a complete set of associated metadata. This, however, is an essential condition for a research-based approach. For the specific field of Greek pottery there is still a lot of work to do on aligning the domain ontology (Gruber and Smith 2015). In 2017, a *repositorium* established at the Institute for the Study of Ancient Culture at the Austrian Academy of Sciences made a start by creating the first publicly accessible database for ancient vases (ODEEG; Lang-Auinger et al. 2021).

7.4.2 Outlook

A main future objective is to enlarge the 3D data volume of digitised Greek vases. Only then the presented analyses and computer-aided exploration can display their full impact in archaeological research. Of course, any development of new digital methods has to consider the integration of the huge amount of existing documentation in previous archaeological publications going back to the nineteenth century, mostly only available in images and text. Novel applications may include cross-modal exploration considering diverse modalities like 3D data, photos, drawings, sketches, metadata at the same time. Thereby, computer-aided methods can help additionally to improve existing documentation in 2D or 3D by measuring data quality (e.g., according to shapes, images or text) and by revealing research/documentation needs.

An interesting outlook is also the introduction of advanced machine learning (ML) methods to the field of Greek pottery studies (cf. Langner et al. 2021). The work described above currently rely on so-called engineered features, which use techniques of traditional image and shape descriptions and segmentations. These approaches are well-understood and in our experience robust in many cases. However, engineered features may be outperformed by learned features, e.g., for retrieval or shape completion tasks (Schreck 2017). In our experience, a challenge is how to extract learned features, given that such approaches require training data and choice of learning architecture and parameters. Training data may be sparse in the domain. More research to this end, e.g., in applying existing ML methods trained for generic images to the archaeology domain using so-called transfer learning, is needed.

7.5 Conclusion

This paper focuses on the research needs in studying CH objects which also includes Greek pottery (vases), a main working field in classical archaeology. A combination of traditional and computer-aided methods is most suitable for a comprehensive exploration of these objects. The traditional methods like hand drawings and sketches, verbal descriptions and the study of publications can be supported by digital methods in many ways; (1) the documentation of a single vase is enriched by digitisation, e.g., specifically by the use of 3D models; (2) the search for comparable material in a wide range of publications is improved by segmentation and retrieval techniques; and finally, (3) visualisation technologies support effective exploration of object repositories and finding correspondences, and enhance the demonstration of research results in publications.

With the above presented case studies we have shown that digitised object data can be a fundamental enhancement for archaeological research. Some approaches are still at the beginning of their development and need further development and more testing. Above all, the targeted digitisation is a basic requirement to advance archaeological research in the field of Greek vases.

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References

Adams WY, Adams EW (2008) Archaeological typology and practical reality. A dialectical approach to artifact classification and sorting, Digitally printed version. Cambridge University Press, Cambridge

Attalla E, Siy P (2005) Robust shape similarity retrieval based on contour segmentation polygonal multiresolution and elastic matching. Pattern Recogn 38:2229–2241

Belongie S, Malik J, Puzicha J (2002) Shape matching and object recognition using shape contexts. IEEE Trans Pattern Anal Mach Intell 24:509–522

Biasotti S, Thompson E, Spagnuolo M (2019) Context-adaptive navigation of 3D model collections. Comput Graph 79:1–13. https://doi.org/10.1016/j.cag.2018.12.004

Boardman J (2001) The history of Greek vases: potters, painters, and pictures. Thames & Hudson, London

Bogacz B, Feldmann F, Prager C, Mara H (2018) Visualizing networks of Maya Glyphs by clustering subglyphs. In: Sablatnig R, Wimmer M (eds) 16th Eurographics workshop on graphics and cultural heritage (GCH), Vienna, November 12–15, 2018. The Eurographics Association, pp 105–111. https://diglib.eg.org/handle/10.2312/gch20181346

Breuckmann B, Karl S, Trinkl E (2013) Digitising ancient pottery. Precision in 3D, Forum Archaeologiae 66/III/2013. http://farch.net

Büsing H (1982) Metrologische Beiträge. Jahrbuch des Deutschen Archäologischen Instituts 97:1–45

Carmignato S, Dewulf W, Leach R (eds) (2018) Industrial X-ray computed tomography. Springer, Cham

Dalal N, Triggs B (2005) Histograms of oriented gradients for human detection. In: Schmid C, Soatto S, Tomasi C (eds) Proceedings. 2005 IEEE computer society conference on computer vision and pattern recognition (CVPR'05), vol 1. IEEE, Los Alamitos, pp 886–893. https://doi.org/10.1109/CVPR.2005.177

de Beenhouwer J (2008) Data management for moulded ceramics and digital image comparison. A case study of Roman terra cotta figurines. In: Posluschny A, Lambers K, Herzog I (eds) Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA'07), Berlin, April 2–6, 2007, Kolloquien zur Vor- und Frühgeschichte 10. Dr. Rudolf Habelt GmbH, Bonn, pp 160–163

Dey S (2018) Potential and limitations of 3D digital methods applied to ancient cultural heritage: insights from a professional 3D practitioner. In: Kelley K, Wood RKL (eds) Digital imaging of artefacts: developments in methods and aims. Archaeopress, Oxford, pp 5–35

Engels L, Bavay L, Tsingarida A (2013) Calculating vessel capacities: a new web-based solution. In: Tsingarida A (ed) Shapes and uses of Greek Vases. Musées royaux d'Art et d'Histoire, Brussels, pp 129–134

Felicísimo ÁM (2011) Vase rollout photography using digital reflex cameras. Tech Briefs Hist Archaeol 6:28–32

Felzenszwalb PF, Huttenlocher DP (2004) Efficient graph-based image segmentation. Int J Comput Vis 59:167–181

Flashar M (ed) (2000) Europa à la grecque. Vasen machen Mode. Biering & Brinkmann, München

Floater MS, Hormann K (2005) Surface parameterization: a tutorial and survey. In: Dodgson NA, Floater MS, Sabin MA (eds) Advances in multiresolution for geometric modelling. Springer, Berlin/Heidelberg, pp 157–186

Frischer B (2014) 3D data capture, restoration and online publication of sculpture. In: Remondino F, Campana S (eds) 3D recording and modelling in archaeology and cultural heritage, Oxford, vol 2014, pp 137–144

Gassner V (2003) Materielle Kultur und kulturelle Identität in Elea in spätarchaischer-frühklassischer Zeit. Untersuchungen zur Gefäß- und Baukeramik aus der Unterstadt. Velia-Studien 2, Wien

Girardeau-Montaut D et al (2021) CloudCompare. https://www.danielgm.net/cc. Accessed 29 Jan 2021

Gruber E, Smith TJ (2015) Linked open Greek pottery. In: Giligny F, Djindjian F, Costa L, Moscati P, Robert S (eds) 21st century archaeology: concepts, methods and tools, Proceedings of the 42nd annual conference on computer applications and quantitative methods in archaeology (CAA'14), Paris, April 22–25, 2014. Archaeopress, Oxford, pp 205–214

Hess M (2017) 3D laser scanning. In: Bentkowska-Kafel A, MacDonald L (eds) Digital techniques for documenting and preserving cultural heritage, Leeds, pp 199–206. https://scholarworks.wmich.edu/mip_arc_cdh/1/

Hess M, Green S (2017) Structure from motion. In: Bentkowska-Kafel A, MacDonald L (eds) Digital techniques for documenting and preserving cultural heritage, Leeds, pp 243–246. https://scholarworks.wmich.edu/mip_arc_cdh/1/

Karl S, Jungblut D, Rosc J (2013) Berührungsfreie und nicht invasive Untersuchung antiker Keramik mittels industrieller Röntgen-Computertomografie. Mit einem Beitrag von Rudolf Erlach. In: Trinkl E (ed) Interdisziplinäre Dokumentations- und Visualisierungsmethoden, Corpus Vasorum Antiquorum Österreich, Beiheft 1. Verlag der ÖAW, Vienna, pp 73–114. http://epub.oeaw.ac.at/7145-4inhalt

Karl S, Jungblut D, Mara H, Wittum G, Krömker S (2014) Insights into manufacturing techniques of archaeological pottery: industrial X-ray computed tomography as a tool in the examination of cultural material. In: Martinón-Torres M (ed) Craft and science: international perspectives on archaeological ceramics, 10th European meeting on ancient ceramics (EMAC'09) London, 10.–13.09.2009. UCL Qatar Series in Archaeology and Cultural Heritage, QScience, Doha, pp 253–261. https://www.qscience.com/content/book/9789927101755

Karl S, Kazimierski KS, Hauzenberger CA (2018) An interdisciplinary approach to studying archaeological vase paintings using computed tomography combined with mineralogical and geochemical methods. A Corinthian alabastron by the Erlenmeyer Painter revisited. J Cult Herit 31:63–71. https://doi.org/10.1016/j.culher.2017.10.012

Karl S, Bayer P, Márton A, Mara H (2019) Advanced documentation methods in studying Corinthian black-figure vase painting. In: Börner W, Uhlirz S (eds) Digitize: research – record – reactivate – reconstruct, proceedings of the 23rd international conference on cultural heritage and new technologies 2018 (CHNT 23), Vienna, November 12.–15. 2018. Museen der Stadt Wien – Stadtarchäologie, Vienna, pp 1–13. https://www.chnt.at/wp-content/uploads/eBook_CHNT23_Karl.pdf

Karl S, Houska P, Lengauer S, Haring J, Trinkl E, Preiner R (2022) Advances in digital pottery analysis. Information Technology 64(6):195–216. https://doi.org/10.1515/itit-2022-0006

Kästner U, Saunders D (eds) (2016) Dangerous perfection. Ancient Funerary Vases from Southern Italy. Getty Publications, Los Angeles

Kazimierski KS, Karl S (2015) CT und archäologische Keramik. "Darf es auch etwas mehr sein?". Fachgespräch "Computertomografie und Archäologie" am 7. April 2016 in Graz. E-Book-Version der Fundberichte aus Österreich 54:D63–D72

Koutsoudis A, Vidmar B, Arnaoutoglou F (2013) Performance evaluation of a multi-image 3D reconstruction software on a low-feature artefact. J Archaeol Sci 40(12):4450–4456. https://doi.org/10.1016/j.jas.2013.07.007

Kozatsas J, Kotsakis K, Sagris D, David K (2018) Inside out: Assessing pottery forming techniques with micro-CT scanning. An example from Middle Neolithic Thessaly. J Archaeol Sci 100:102–119. https://doi.org/10.1016/j.jas.2018.10.007

Lang-Auinger C et al (2021) ODEEG (2017–2019). ODEEG. Online database for research on the development of pottery shapes and capacities. https://odeeg.acdh.oeaw.ac.at. Accessed 29 Jan 2021

Langner M (2020) Die Materialität und Objektevidenz griechischer Vasen. In: Langner M, Schmidt S (eds) Die Materialität griechischer Vasen, Mikrohistorische Perspektiven in der Vasenforschung, CVA Deutschland Beiheft 9. Beck, München, pp 9–13

Langner M et al (2021) EGRAPHSEN. Possibilities and perspectives of the digital painter attribution for attic vases. https://www.uni-goettingen.de/en/598165.html. Accessed 29 Jan 2021

Lengauer S, Komar A, Labrada A, Karl S, Trinkl E, Preiner R, Bustos B, Schreck T (2019) Motif-driven retrieval of Greek painted pottery, accepted. In: Rizvic S, Rodriguez Echavarria K (eds) 17th Eurographics workshop on graphics and cultural heritage (GCH), Sarajevo, November 6–9, 2019. The Eurographics Association, pp 89–98. https://doi.org/10.2312/gch.20191354

Lengauer S, Komar A, Labrada A, Karl S, Trinkl E, Preiner R, Bustos B, Schreck T (2020) A sketch-aided retrieval approach for incomplete 3D objects. Comput Graph 87(2020):111–122. https://doi.org/10.1016/j.cag.2020.02.001

Lenormant D, de Witte J (1858) Élite des monuments céramographiques III. Leleux, Paris

Lieberwirth U, Herzog I (eds) (2016) 3D-Anwendungen in der Archäologie. Computeranwendungen und quantitative Methoden in der Archäologie. Workshop der AG CAA und des Exzellenzclusters Topoi 2013. Edition Topoi, Berlin. https://doi.org/10.17171/3-34

Lu M, Zhang Y, Zheng B, Masuda T, Ono S, Oishi T, Sengoku-Haga K, Ikeuchi K (2013) Portrait sculptures of Augustus: categorization via local shape comparison. In: Digital Heritage International Congress, Marseille 2013. 2014. https://doi.org/10.1109/DigitalHeritage.2013.6743812

Mannack T et al (2024) Beazley Archive Pottery Database. https://www.carc.ox.ac.uk/carc/pottery. Accessed 25 Jan 2024

Mara H, Portl J (2013) Acquisition and documentation of vessels using high-resolution 3D-scanners. In: Trinkl E (ed) Interdisziplinäre Dokumentations- und Visualisierungsmethoden, Corpus Vasorum Antiquorum Österreich, Beiheft 1. Verlag der ÖAW, Vienna, pp 25–40. http://austriaca.at/0xc1aa5576_0x002ec067.pdf

Mara H et al (2021) GigaMesh Software Framework. https://gigamesh.eu. Accessed 29 Jan 2021

Moreno E, Arévalo A, Moreno JF (2018) From traditional to computational archaeology. An interdisciplinary method and new approach to volume and weight quantification. Oxf J Archaeol 37:411–428. https://doi.org/10.1111/ojoa.12149

Nocerino E, Rieke-Zapp DH, Trinkl E, Rosenbauer R, Farella EM, Morabito D, Remondino F (2018) Mapping VIS and UVL imagery on 3D geometry for non-invasive, non-contact analysis of a Vase, ISPRS Riva 2018, pp 773–780. https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2/773/2018/isprs-archives-XLII-2-773-2018.pdf

Nørskov V (2002) Greek vases in new contexts: the collecting and trading of Greek vases: an aspect of the modern reception of antiquity. Aarhus University Press, Aarhus

Pintus R, Pal K, Yang Y, Weyrich T, Gobbetti E, Rushmeier H (2016) A survey of geometric analysis in cultural heritage. Comp Graph Forum 35:4–31. https://doi.org/10.1111/cgf.12668

Preiner R, Karl S, Bayer P, Schreck T (2018) Elastic flattening of painted pottery surfaces. In: Sablatnig R, Wimmer M (eds), 16th Eurographics workshop on graphics and cultural heritage (GCH), Vienna, November 12–15, 2018. The Eurographics association, pp 165–168. https://doi.org/10.2312/gch.20181355

Preiner R, Schmidt J, Krösl K, Schreck T, Mistelbauer G (2020) Augmenting node-link diagrams with topographic attribute maps. In: Proc. EuroVis 2020, Computer Graphics Forum 38(4):35:1–35:1. https://doi.org/10.1111/cgf.13987

Quattrini R, Ramona R, Pierdicca R, Paolanti M, Clini R, Nespeca R, Frontoni E (2020) Digital interaction with 3D archaeological artefacts: evaluating user's behaviours at different representation scales. Digit Appl Archaeol Cultural Herit 18:e00148. https://doi.org/10.1016/j.daach.2020.e00148

Rice PM (2015) Pottery analysis. A sourcebook, 2nd edn. University of Chicago Press, Chicago/London

Rieck B, Mara H, Krömker S (2013) Unwrapping highly-detailed 3D meshes of rotation-ally symmetric man-made objects. In: Grussenmeyer P (ed) XXIV international CIPA symposium, 2–6 September 2013, Strasbourg, vol II-5/W1. ISPRS Annals of the Photogrammetry, Remote Sensing and SIS, pp 259–264. https://doi.org/10.5194/isprsannals-II-5-W1-259-2013

Rieke-Zapp D, Royo S (2017) Structured light 3D scanning. In: Bentkowska-Kafel A, MacDonald L (eds) Digital techniques for documenting and preserving cultural heritage. Arc Humanities Press, Leeds, pp 247–251. https://scholarworks.wmich.edu/mip_arc_cdh/1/

Rostami R, Bashiri FS, Rostami B, Yu Z (2018) A survey on data-driven 3D shape descriptors. Comp Graph Forum 38:356–393. https://doi.org/10.1111/cgf.13536

Santos P, Ritz M, Tausch R, Schmedt H, Monroy R, De Stefano A, Posniak O, Fuhrmann C, Fellner D (2014) CultLab3D – on the verge of 3D mass digitization. In: Proceedings of GCH Workshop on Graphics and Cultural Heritage, Eurographics 2014. https://doi.org/10.2312/gch.20141305

Schreck T (2017) What features can tell us about shape. IEEE Comput Graph Appl 37:82–87

Schreck et al (2021) Crossmodal Search and Visual Exploration of 3D Cultural Heritage Objects. https://www.tugraz.at/institute/cgv/research/projects/crosssave-ch/. Accessed 29 Jan 2021

Sheffer A, Praun E, Rose K (2006) Mesh parameterization methods and their applications. Found Trends® Comp Graph Vision 2(2):105–171. https://doi.org/10.1561/0600000011

Snyder JP (1993) Flattening the earth: two thousand years of map projections. University of Chicago Press, Chicago

Spelitz S, Moitinho de Almeida V, Lang-Auinger C (2020) Automatic geometry, metrology, and visualisation techniques for 3D scanned vessels. Digit Appl Archaeol Cultural Herit 17:e00105. https://doi.org/10.1016/j.daach.2019.e00105

Trinkl E (2011) Corpus Vasorum Antiquorum Österreich 5, Kunsthistorisches Museum 5. Verlage der ÖAW, Wien

Trinkl E, Rieke-Zapp D (2018) Digitale Analyse antiker Kopfgefäße. In: Schöne-Denkinger A, Corpus Vasorum Antiquorum Deutschland, Berlin 18. Beck, München, pp 68–73

Trinkl E, Rieke-Zapp D, Homer L (2018) Face to face – considering the moulding of Attic head vases reconsidering Beazley's groups by quantitative analysis. J Archaeol Sci Rep 21:1019–1024. https://doi.org/10.1016/j.jasrep.2017.07.023

Tsingarida et al (2021) Calcul de capacité d'un récipient à partir de son profil. http://capacity.ulb.ac.be. Accessed 29 Jan 2021

Van de Put WDJ (1996) The use of computer tomography for the study of Greek ceramics. In: The J. L. Theodor collection of attic black-figure vases, Allard Pierson Series 10. Allard Pierson Museum, Amsterdam, pp 203–205

Van de Put WDJ (2006) Corpus Vasorum Antiquarum, The Netherlands 10, Amsterdam 4. Allard Pierson Museum, Amsterdam

Van der Maaten L, Boon P, Lange G, Paijmans H, Postma E (2007) Computer vision and machine learning for archaeology. In: Clark JT, Hagemeister M (eds) Digital discovery, Exploring new Frontiers in human heritage, computer applications and quantitative methods in archaeology, proceedings of the 34th conference (CAA'06), Fargo, United States, April 18–21, 2006. Archaeolingua, Budapest, pp 476–482

Villard F (1965) Corpus Vasorum Antiquorum, France 21, Musée du Louvre 13. H. Champion Paris.

Walter C (2008) Towards a more 'scientific' archaeological tool. The accurate drawing of Greek vases between the end of the nineteenth and the first half of the twentieth centuries. In: Schlanger N, Nordbladh J (eds) Archives, ancestors, practices: archaeology in the light of its history. Berghahn Books, New York, pp 179–190

Windhager F, Salisu S, Leite RA, Filipov V, Miksch S, Schreder G, Mayr E (2020) Many views are not enough: designing for synoptic insights in cultural collections. IEEE Comput Graph Appl 40:58–71

Part IV

Giving Access

Chapter 8
Balancing Data Storage and User Functionality: The 3D and Archaeological Data Strategy of the Tracing the Potter's Wheel Knowledge Hub

Loes Opgenhaffen, Caroline Jeffra, and Jill Hilditch

Abstract The Tracing the Potter's Wheel (TPW) project is designed to identify and assess the appearance of the potter's wheel as a technological innovation within the Bronze Age Aegean through the integration of experimental, analytical and digital archaeological approaches. A major output of the project is a technologically-focused archive that collates, presents and enhances research data about forming technology for archaeological and experimental ceramics. Another important project aim is to untangle relational and contextually-rich data storage for 3D models, with a particular focus on both metadata and paradata. Moreover, by disentangling the 3D models and treating them as an integrated part of the archive rather than a separately presented class, the project's active, multivocal knowledge base explicitly integrates the often-separated complementary perspectives on archaeological datasets, dubbed the TPW Knowledge Hub. To reach these divergent yet intricate objectives, TPW introduces the approach of designerly thinking into digital archaeological practice for the design of a user-focused interface to share information and knowledge with peers and the general public. Ultimately, the TPW archive serves as a dynamic learning tool uniting archaeological data storage with additional open-access publications and resources.

Keywords Reproducibility · Designerly thinking · Knowledge base · 3D models · Multivocality

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8.1 Introduction

Tracing the Potter's Wheel (TPW) is a five-year research project funded by the Dutch Research Council (NWO). The project is designed to identify and assess the appearance of the potter's wheel as a technological innovation within the Bronze Age Aegean (2500–1200 BC) through the integration of experimental, analytical and digital archaeological approaches. A major output of the project is an archive which captures and shares technologically-focused information about forming techniques for archaeological and experimental ceramics. From the outset, the project archive was designed to assist and enhance project research while simultaneously sharing data and knowledge with peers and the general public. In this light, the TPW archive has been designed as a dynamic learning tool which marries the stable storage of digital pottery information with a user-focused interface, complemented with additional open-access publications and resources. The project has also grappled with designing relational and contextually-rich data storage for 3D models and their associated information, particularly both metadata and paradata. 3D models are treated in this approach as an integrated part of the archive instead as a separately presented class. This diverse approach to data storage, knowledge and learning has coalesced into the TPW Knowledge Hub. The design and functionality of TPW's active, multivocal research knowledge hub is worthy of further discussion as it explicitly integrates these often-separated complementary perspectives on the archaeological data.

8.2 Taking Up Challenges and Forging Strategies

A number of specific challenges exist in relation to the Tracing the Potter's Wheel Project's goals for creating a stable and user-friendly repository of pottery records. These included the nature of the data types the archive is composed of, the interest in being guided by design thinking, and the project's understanding of the nature of a 'common vision' in pottery archives. Design thinking has a different approach from the usual problem-solving technocentric approach. Instead, it revolves around the idea of problem-finding from a human-centered approach (Clarke 2019, p. 13), seeking to locate the needs and understand the issue in the system that users are struggling with before then solving the technical problem. In other words the developer never starts with the solution, but starts "determining what basic, fundamental issue[s] need to be addressed" and then "consider[s] a wide range of potential solutions" (Norman 2013, p. 219). Design thinking consists of a series of challenges, some exciting, others more of a drawback, that also form opportunities as well and which occur within a social group. The design process can be divided into iterative but non-linear, reflexive phases. These phases include, but are not limited to: understanding the data types and users (visualised through a data wireframe, for example); observations of the circumstances (through comparison against other archives and platforms for data models and user experience); functionality assessment; prototyping (through which several designs are developed); as well as the actual building, testing, and launching of the database. This multifaceted approach to problems, or challenges, is a creative practice. A key benefit of this iterative process is that, when practiced in a transparent and coherent way, it can be applied by others and developed accordingly (see also *Ideo*).

In order to develop the archive platform, TPW sought the partnership of commercial developers, funded by a Dutch Data Archiving and Networking Service (DANS) Small Data Project grant (Klein Data Project, KDP). TPW's partners at KBELL & POSTMAN (https://kbellpostman.com/) employ a *design thinking* approach from a creative, user-oriented perspective, modelling and modifying from experiment and experience with a wide range of users. Within this partnership, the TPW team takes an academic stance, just as scientists take a more formal strategy towards problem solving, the goal of which is to learn from these attempts (Sarwar and Fraser 2019, p. 345). This is perhaps more properly called *designerly thinking*, which "links theory and practice from a design perspective" (Johansson-Sköldberg et al. 2013, p. 123). This leans more to the 'layers of design' practice as formulated by Lawson and Dorst 2009 (Dorst 2011, p. 526), which is focussed on project, process and 'field' (Bourdieu et al. 1999, cited by Dorst 2011, p. 526), or social context. The latter stands for a more deliberate way of reasoning in which diverse social groups are taken into account. Furthermore, it reflects on project-specific methods of data collection as well as the way that data is disseminated as meaningful archaeological information. Through the archive, knowledge is produced while mechanisms of receiving new data and knowledge from other disciplines are nurtured. This collaboration between commercial developers and academic researchers working under the umbrella of design thinking is very fruitful in the development of a dynamic archive that suits the project and a wide range of targeted users.

The agile and particularly reflexive approach that design thinking can bring to archaeological practice is not restricted to the digital realm alone: problems such as data uncertainty already exist in the practice of collecting, recording and digitisation. The choice of what data to collect, what research is deemed interesting and informative in the first place (and which is negotiated over time, as argued by Börjesson and Huvila 2018, p. 14) is the basis of a database structure, and furthermore has an impact on archaeological knowledge-making. The first problem is encountered in the collecting phase: the ambiguous nature of archaeological data, being often fragmented and incomplete. Fragmentation and incompleteness are not appreciated in creating data models. Further, uncertainty about an object's specific forming method or a precise chronological date is hard to capture within a database model, let alone to query (Piotrowski 2019). Another frequent problem arises when data is collected under different circumstances and through different strategies, which can lead to inconsistencies in data patterns and resulting data accuracy. And although most data in the TPW project has been analysed and collected by the project members themselves, some data depends on archival data produced by other specialists that was recorded differently, impeding comparability and reproducibility (a pitfall described by Boast and Biehl 2011, p. 128). These inconsistent datasets are then difficult to compare, resulting in uncertain outcomes. TPW has overcome this problem by forging a strategy for the selection and recording prior to digitisation and manipulation, or ‘data context’ (Huggett 2020, S12), which was applied during fieldwork and at diverse locations (see Fig. 8.1). This overarching strategy steers the selection procedure, description and photographic procedure, the standardisation of equipment, and 3D recording procedure and related metadata standardisation for the analogue and digital recording processes. Many potential data uncertainties are prevented by this consistent strategy. It should become apparent during the planned later phase of the database, when other specialists and projects begin to contribute a dataset to the TPW archive, that following the same selection, collection and digitalisation procedure is crucial. In this way it is possible to safeguard data accuracy, meaningful re-use and assembly of data and subsequent comparative analysis that form the basis of archaeological knowledge production.

Over the course of fieldwork and analysis, TPW has generated considerable data, composed of multiple file types for images, video footage, 3D models, and texts, as well as the contextual information for those files, including metadata and paradata. This large volume of data is, in fact, representative of a relatively small number of archaeological and experimental objects. But each object included in the database has its own solar system of associated data files which provide different perspectives on the object represented. Taken together, these many solar systems of data files, create a galaxy of relations between the objects. Although the objects studied are not the totality of the objects from any one site’s ceramic assemblage, by capturing information about objects scattered across the universe of an assemblage, it is possible to understand some of the key features of that universe. These data represent a multiplicity of complementary perspectives on the objects themselves. In effect, data was collected in different formats to gain different insights into the nature of a number of specific archaeological and experimental pots (see Fig. 8.2). This challenge was an important one to meet, because the value of making such an archive is the presentation of this complementary information in its context; file types need seamless interconnections to illustrate different points. A major difference between this archive and others is the integration of 3D models alongside other types of object representation; presenting all these different file formats side-by-side is essential for illustrating the complexity of that object. Additionally, this project does capture and present information about different kinds of pottery. The specific needs for presenting an archaeologically-retrieved object are different from presenting an experimentally-produced object and, as such, the kinds of information which populate the context also differ.

8.3 Current Solutions for 3D Models in Archives

Today, digital 3D technology is applied in virtually every sub-discipline to document, analyse and (re)present archaeological data and heritage. Many archaeological 3D datasets are now available online and are often held up as examples of the

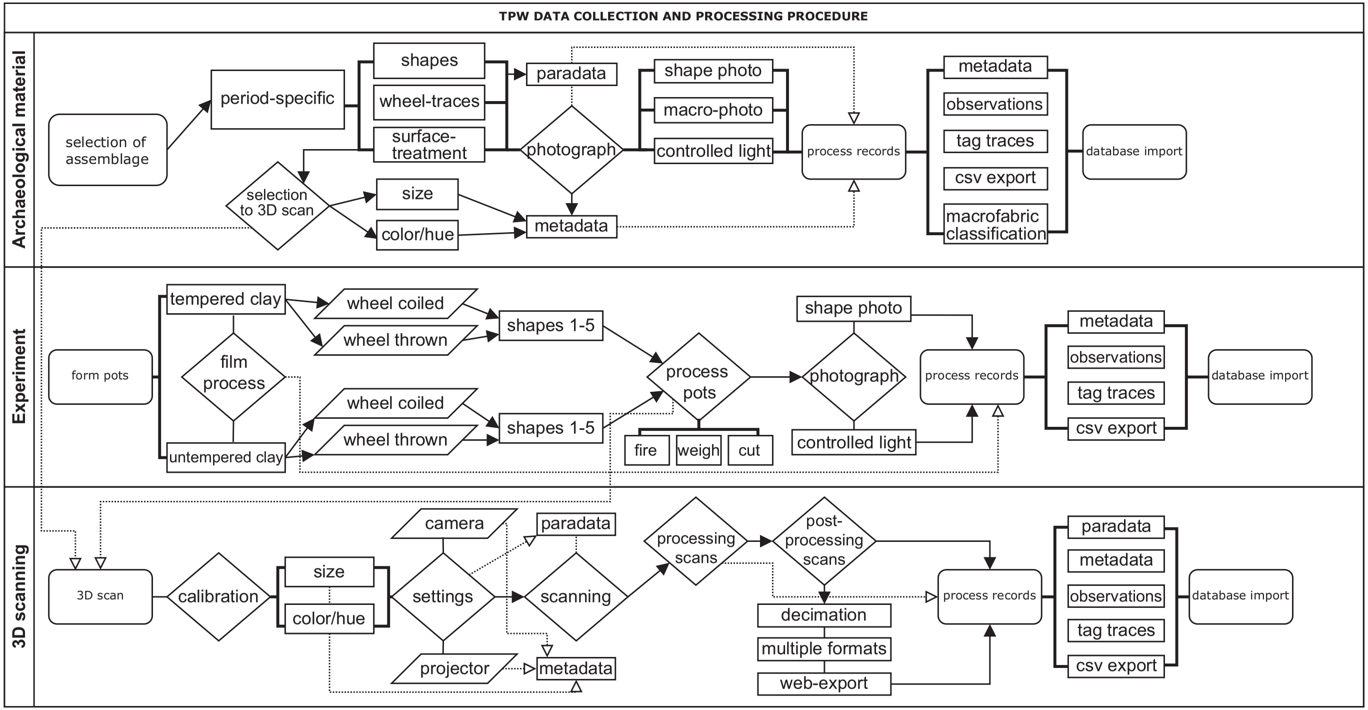

Fig. 8.1 Diagram representing the data collection and processing procedure. (Image: L. Opgenhaffen)

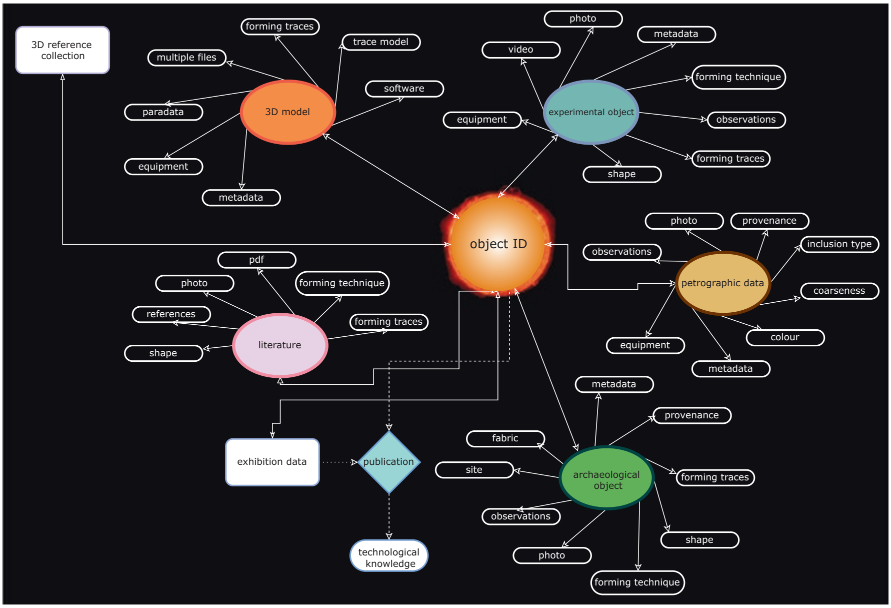

Fig. 8.2 TPW data types, data and metadata contexts represented as an interconnected constellation orbiting the object ID. (Image: L. Opgenhaffen)

democratisation of data and knowledge production. However, the standard varies considerably, as revealed in an exploration carried out by the TPW team into 3D repositories and online pottery archives. Our observations support the results of a thorough survey of '3D' digital heritage repositories and platforms by Champion and Rahaman (2020), and the study by Statham (2019), which offers a comparative analysis of several 3D platforms and their relation to prevailing international guidelines for preserving heritage (ICOMOS and UNESCO *and* the London Charter and Seville Principles). Few of these platforms have significant user participation or even interactive tools, nor do they have the possibility to annotate or contextualise the 3D content. Actual engagement by users through interaction with the model for topography or stylistic exploration, or by interrogating the underlying data – functionality for comparing 3D models (also with other media) and allowing comments or contribution of similar datasets – are virtually absent in these repositories. The democratisation seems therefore to take a one-way direction.

8.3.1 Digital Archives and Platforms

An increasing number of pottery databases are appearing online, which is a positive development. While in the early years of digitisation pottery archives tended towards a digital replication of a traditional catalogue (such as the Beazley Archive), an increasing number of initiatives aim to move beyond mere cataloguing and provide active repositories supported by rich media, tools to compare and study objects, and semantic searches. These projects, such as ArchAIDE and the Levantine Ceramics Project, have rich databases and appealing, clearly structured websites. ArchAIDE in particular has easy search functionality, associated vessel display, and has integrated 3D models with accompanying metadata through 3DHOP, and a tool to automatically identify pottery shapes. Other promising online platforms for pottery identification, 3D visualisation and comparative analysis were the *Pottery Informatics Query Database* (PIQD, Smith et al. 2014), that aimed to go beyond digital archiving and presented itself as online, open-source tool to automatically extract data from scanned potsherds and provide rich (3D) contextual information. In 2015 it joined the CRANE project, after which it withered. Another platform is the EU funded project GRAVITATE-EU, which is building a digital platform that offers tools for reassembling fragmented material, shape analysis and comparative analysis based on 3D geometry and semantic data. A brief survey of online pottery databases leads to the conclusion that, besides some promising platforms as mentioned above, the level of data literacy, especially when it comes to visualisation and user experience, is markedly low. Indeed, it seems that these two concepts are fundamentally linked: if visual files are not immediately accessible and only lists of information are visible, then records are usually only accessible to specialists, due to reduced searchability and potential for comparative analysis. In this sense, these websites have poorly-considered design, which leads to reduced navigability and often prevents non-experts from querying the database. Another function which is often lacking is annotation of the 3D models, which improves their contextualisation and searchability, but is also critical for accessibility and comparative analysis, for specialists and non-specialists alike. Lastly, very few websites allow for comments on their data (however, The British Museum online catalogue is one of the few to allow this function), another important element in stimulating comparative analysis.

Pottery, and especially past potting practice, seems not to be the first choice for constructing and testing versatile 3D archives. A strong focus on disseminating research and cultural heritage in 3D is in excavation, architecture and 3D documentation of special finds. Good examples of digital archives with embedded 3D viewers include Dynamic Collections and 3D Icons Ireland. The former uses 3DHOP to visualize, annotate and query artefacts from a reference collection, with familiar tools to the archaeologist such as lighting, measuring and sectioning, and to freely rotate the object. The system serves as an excellent complementary learning tool alongside the physical collection and has the functionality that allows students and other stakeholders to create their own collections, and to tag and make notes in an on the artefact, which can then be saved and shared as a json file (Ekengren et al. 2021). The latter project uses Sketchfab as an embedded viewer in a data structure that reads as an article, accompanied with other media. This narrative presentation of archaeological data common to projects is beneficial for users who might be unfamiliar with specialist catalogues and lists of raw data. This can be compared against the presentation of the Cinema Parisien in 3D reconstruction, carried out by researchers working within the framework of CREATE (University of Amsterdam). This 3D reconstruction is presented in reasonable quality using the Unity web player and is successfully connected to the database, which enables to request its underlying data (text and images) by freely clicking on any part of the building while walking through the movie theatre. Further, users are given the option of leaving comments (see Noordegraaf et al. 2016 and *Cinema Parisien*; this web application works only with Waterfox and the Unity Web Player).

One example of a digital archive that does focus on potting practice is the Collections de la technothèque, an initiative of the Laboratoire Préhistoire&Technologie (PréTech, UMR 7055, CNRS / Université Paris Nanterre) to open access to the rich research material collections of the experimental and ethnoarchaeological repositories for prehistoric techniques (where the experimental ceramics of TPW member Caroline Jeffra can be found (Jeffra 2011)). Although there are no 3D models within the repository of ceramic forming techniques, their objective in allowing the public to consult their collections remotely, according to their level of interest, mirrors the goal of the TPW digital archive. A final mention should also be made of the ARKEOTEK organisation and associated online journal, which partners with PréTech to provide "un accès en ligne à ces collections référentielles qui constituent d'indispensables outils d'expertise" [online access to these reference collections, which constitute essential tools of expertise] (*PréTech*). Although it does not support 3D content, nor does it have a multivocal aim in addressing lay audiences, the core objective of ARKEOTEK was to create a knowledge base centred on the 'archaeology of techniques'. Here, experts share their research through the publication of not only datasets and results, but also the reasoning processes built upon them (Gardin and Roux 2004, p. 29), based upon the Scientific Construct and Data (SCD) format designed by Philippe Blasco. This practice-centred perspective is further elaborated by Dallas, who maintains the importance of not only the research dataset but also "processes related to the production of knowledge, its public communication and user experience in digital curation" (Dallas 2015, p. 192). It is this orientation which has informed the foundation of the TPW database.

There are few nationally-funded initiatives for managing this type of research-driven 3D data. One notable exception is the Archaeological Data Service (ADS) which has an embedded 3D viewer similar to 3DHOP (the same developers are behind it). ADS provides a highly detailed metadata-scheme (available via *ADS metadata scheme*) to record data-retrieval, postprocessing and technical specifications. Furthermore, ADS does not treat 3D data as a separate class or collection; rather it is integrated into the repository with an impressive level of flexibility in how a project can choose to present their 3D data.

On an international level, Europeana provides a platform on which European cultural data is displayed (but not hosted). By engaging with wider-ranging efforts such as these, there is less risk for projects of falling into obsolescence. Europeana does not support 3D content itself, instead relying on embedded viewers such as Sketchfab. Another supported format was 3D PDF, a promising format a decade ago but, as Flash is no longer supported, the 3D content can no longer be navigated online. For 3D models, Europeana has now the app Share3D (available at https://share3d.eu/, not to be confused with Share3D.com) to link Sketchfab models and submit (limited) metadata to Europeana. In the dashboard, the metadata can be adjusted to Europeana standards, though these standards are not directly accessible, as entries must be shared with Europeana via an approved aggregator. In the case of archaeological material, CARARE is Europeana's designated aggregator. This is a suitable solution if projects have few 3D models, but with larger 3D datasets this cumbersome pipeline of Share3D can be a huge and laborious task. Furthermore, the services provided by many aggregators incur yearly costs, an issue which has repercussions for the long-term sharing of data beyond the life of temporary projects.

With the exception of rare examples such as those described above, 3D models are still most often set apart as a visual data class, presented apart from other contextual data in '3D collections' within projects and project databases. 3D datasets should not be presented in isolation, and solutions must be crafted which integrate 3D models within archives while giving due attention to user experience of those archives. A 3D model only becomes a meaningful visualisation when embedded within its contextual information. Projects which fail to recognise this risk returning archaeologists into object-focussed antiquarians.

8.3.2 Viewers: Sketchfab and 3DHOP

A significant technical hurdle to fully integrating 3D models within a user-experience designed archive is the limited range of available viewers for embedding and presenting those models. The TPW Knowledge Hub is not exclusively a 3D archive presenting an exciting 3D collection, instead it is an archaeological narrative about past pottery technology and social interaction in which the 3D models are an integral part. For this reason, the 3D viewer must integrate seamlessly with other types of data presentation, allowing interconnections with those data and their corresponding file types. A number of essential functions have proven useful for including models within the archive. These include tagging and presentation tools, embedded analytical tools, and easy download options. These functions play an important role in allowing users to more fully interrogate the material based upon their observations in the models and other media shown alongside them.

8.3.2.1 Tagging and Presenting Models

A 3D model is not self-explanatory; tagging functionality embeds a 3D models contextual information within the model itself, rendering it a meaningful object. In doing so, tagging enriches the model and makes it a meaningful scientific representation of archaeological knowledge. Yet, the diversity of tagging and presentation needs for the field of archaeology may make it resistant to standardisation; it depends heavily upon the aims of the visualisation, which can be a 3D model of a

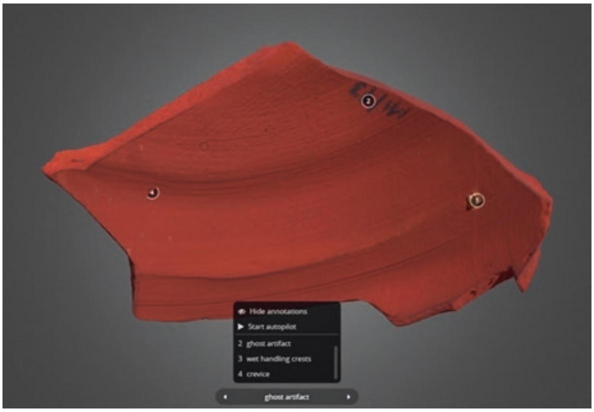

Fig. 8.3 Example of an annotated 3D model revealing information about both forming traces and 'ghost artefacts': https://sketchfab.com/3d-models/m1-73-002dec-676cb1d9ae11431498544a98911d97bb

monument, a multilayered excavation, or fragmented artefacts. Tagging also depends on many other related factors, from recording to presentation, and even teaching.

In the case of research in pottery forming technology, tags provide targeted description of specific model attributes, both relating to the data collection process as well as the morphology of the object being visualised. For example, TPW's SketchFab models often indicate the presence of forming traces, such as crevices, alongside 'ghost artefacts' such as inward-projecting surface topography on a model where the physical object was darker in colour (Fig. 8.3). Tagging furthers the aim of integrating models alongside other methods of data presentation (such as text, photographs and video). Sketchfab achieves this by providing user-friendly tagging functionality which can include links to related data, texts, and media within the database and to other websites. This enriches the model, making it informative and giving it a meaningful voice. Users can be guided in what to see and thus be informed, in the TPW case, about forming traces. In comparison, 3DHOP's tagging functionality is significantly less user-friendly, as the 'hotspot' needs to be assigned in the code, a time-consuming task which is beyond the skill set of many archaeologists.

8.3.2.2 Analytical Tools in Model Viewers

There are a number of analytical tools which archaeologists use when directly handling objects, and some similar functionality is available for interacting with 3D models. Sketchfab's most archaeologically-useful analytical tools are the matcap function in the model inspector, which enables turning off the texture, and the directional light tool, which both enable to inspect morphological features in more detail. It does not have a measuring tool, however, and a sense of scale is only possible if a scale bar is uploaded with the model. 3DHOP, on the other hand, provides a toolkit that enables detailed simulation of the physical analysis workflow. This functionality includes a torch to illuminate specific parts of the object, an option to turn the texture off, a measuring tool, and the possibility to make sections on different planes. The familiarity of these tools, and the expansion of functionality of matcap or texture removal, strengthens the case for using these viewers for research that enables study of objects which better approximates direct handling of these objects.

8.4 The TPW Pottery Archive

A wide range of online platforms are available, both with and without 3D content, which gives ample opportunity for researching solutions to fit the needs of the TPW Knowledge Hub. This diversity was both motivational and inspirational during the design process, informing the project on avenues to avoid specific problems in data representation, as well as how to address multiple audiences and user needs. Through this research, the need for a tailored solution became clear. Although not currently supporting 3D data, the DANS Small Data Project grant awarded to TPW enabled the project partnership with developers KBELL & POSTMAN for the design of an active archive to be hosted by the University of Amsterdam. These experienced developers give an unique insight into user experience processes beyond the borders of cultural heritage, inspiring TPW to engage in more designerly thinking and reflect on the processes within the project in a more creative way.

As highlighted above, a major difference between the TPW Knowledge Hub and others is the integration of 3D models alongside other types of object representation. Each of the file types, and the types of objects described in those file types, have different metadata needs. Although metadata standards for cultural heritage exist in data models such as Dublin Core and CIDOC CRM, these do not specifically incorporate 3D content needs and requirements. The most important problem in these data models is that there is no clear definition of what kind of entity a 3D model is exactly and how to label it (for an interesting example of such confusion can be found at the CIDOC CRM Issues section: http://www.cidoc-crm.org/Issue/ID-342-3d-model-example-in-p138), and no system to record the metadata of a model yet, although CIDOC CRM is currently developing the CRMdig ontology and RDF Schema to encode metadata about digitisation processes, both 2D and 3D (http://www.cidoc-crm.org/crmdig/). CIDOC is quite prescriptive rather than descriptive, which makes it inflexible and hard to apply in a diverse discipline as archaeology, with divergent (national and institutional) recording and documentation traditions. It proved extremely difficult for TPW's domain-specific pottery manufacturing traces and fabrics classifications to adjust to CIDOC. The Dublin Core is less extensive than the CIDOC CRM and thus more flexible for specific collections and specialisms, while the principle classes are compatible and therefore findable. A final example is the CHARM reference model, a semi-formal abstract reference model with a wide range of different users. CHARM is not prescriptive about too many details; users should define their own particular properties within this data model by using extensions based on ‘object-oriented conceptual modelling principles’ (*CHARM*).

Clearly, work remains to be done to translate these models into domain-specific language for more ready application to archaeological materials, particularly in the case of smaller projects who may not be able to outsource this important aspect of sharing their data. In order to prevent reinventing the wheel, the TPW model will adhere, where possible, to the CIDOC CRM framework while building forth on the concepts of the CHARM model. This approach to data combines prescriptive with descriptive models that will suit our research objectives, contributors and user’s needs, and enables planned integration with Europeana.

The 3D models in the TPW database are classified as a piece of data relating to a physical object. The simple solution is to link the 3D model in the database via the object ID used for the original, archaeological or experimental, object. With that ID, the model will be automatically annotated and linked to its contextual data. This resolves the risk of isolating the 3D model while also preserving the visibility of the technical metadata and paradata about the choices of the archaeological visualiser. This paradata is captured in the workflow description for the entire scanning, processing and post-processing procedure, including choices for particular hardware and software, their settings, as well as parameters such as the decimation algorithms to simplify the models. This workflow is published on the project website (Opgenhaffen 2020a), and video tutorials about specific scanning solutions are in production. This transparency in project workflows and data collection procedures are created with the FAIR principles in mind. TPW values these guiding principles to ensure transparency about data and methodology (Opgenhaffen 2020b), and to keep the data accessible and discoverable at all times (Wilkinson et al. 2016). Moreover, tutorials about workflows and the availability of rich metadata schemes enable the possibility to reproduce data collection and sharing, and to reuse data to increase knowledge about transmission of ancient technology.

TPW is currently using Sketchfab Pro to share and publish the 3D models of the experimental dataset (see Fig. 8.3). Although 3DHOP has better functionality for archaeological inspection, Sketchfab works faster in uploading and tagging the models. Despite Sketchfab being a commercial platform, the Pro version is free of charge for educational institutions. Sketchfab Pro enables models up to 200 MB to be uploaded, which ensures a high degree of geometric data integrity, that is, not too much data is lost when decimating/simplifying the raw files to an acceptable format and size for online display. Indeed, TPW is well aware of the issue of ownership in the case of a profit-oriented enterprise such as Sketchfab, and so hopes to overcome this in the near future through an in-built viewer. The Sketchfab models are embedded in the web interface, and the different file formats of the 3D model are provided as download files, such as the original scandata, the exported OBJs and simplified OBJs, PLY and STL files. Together with the technical metadata and detailed workflow description, the transparency of the entire workflow from scanning through to file processing is guaranteed, as are file compatibility and reproducibility of workflows. The ability to reproduce workflows and reuse original files ensures a

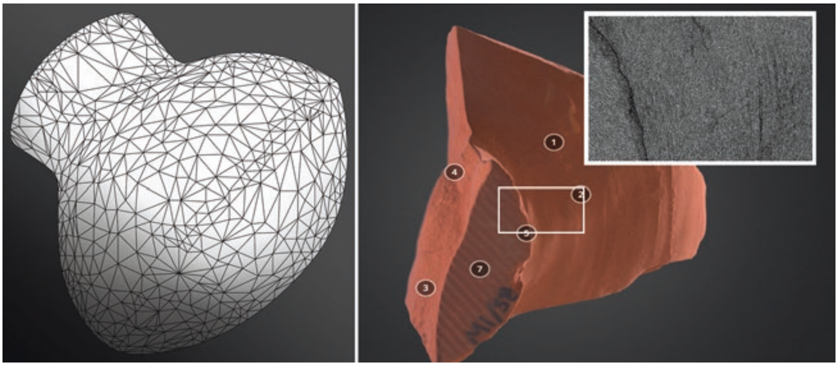

Fig. 8.4 Left: a 3D scan made in 2002 (after Rowe et al. 2002, Fig. 8.1). Right: a 3D scan made in 2018. (Image: L. Opgenhaffen)

consistent accuracy of data quality. Downloads also enable users to conduct further offline analysis, as well as to compare 3D models of artefacts in open source software such as Meshlab. In particular, the 3D models of individual forming trace examples from the unique reference collection developed by TPW can be downloaded and 3D printed to function as a physical training set. Users can then inspect the traces in a tactile way, achieving a better understanding of pottery technology alongside the digital material showing greater contextual information.

An important issue, however, is whether it is possible to maintain the ideal of reuse, reproducibility and data assessment, given that ever increasing scanning resolutions and computing power regularly render hardware and software obsolete. This means the safeguarding of the contextual data is extremely important, as the hardware and 3D models can always be replaced. As an example, 3D models of pottery recorded in the early 2000s, consisting of a few dozen faces, are impossible to compare against 3D models of the same pots made today, which consist of a few million faces (see Fig. 8.4). Similarly, early 3D models do not have the level of detail that is required to identify particular manufacturing traces. Replacement of an early 3D model with a modern 3D scan produced according to the current recording strategy enables a detailed topographical analysis while maintaining the contextual data that was originally documented. The same procedure can be repeated in another two decades.

8.4.1 Archive Architecture

The relational database is built with MySQL, and the platform with PHP (8) on top of the Laravel (8.0) framework. Laravel is a popular open-source PHP-framework providing scaffolding for web applications. This enables modular packages to be built on top of it to manipulate and maintain a web interface while running several applications. This, for example, allows for multiple data sources to be visualised while embedding external viewers. The platform is powered by the search engine Algolia to improve search results and especially ease search queries. It adds a search box to the website front end and supports simple text-based search approaches. As it indexes the TPW site, Algolia offers web search experiences comparable to Shopify webshops, which enables users looking for forming traces of pottery on the internet to find the information in the TPW database more easily and faster.

8.4.2 Static vs Active

From the outset, the TPW Knowledge Hub was designed to facilitate future research into pottery forming techniques. Given the sheer scope of such research, not only in the Bronze Age Aegean but also in regions and periods beyond our TPW remit, it was acknowledged early on in the project that the archive might be supplemented by other reference collections in the future, to consolidate the known repertoire of surface macrotraces that relate to specific forming techniques. As a result, the project aims were adapted to create the foundations for a dynamic knowledge hub of wheel-formed pottery that could be extended to increase knowledge about past potting technology and technological transfer thanks to cutting-edge digital technology. Such functionality requires an archive that can be *actively* added to, or updated, through the inclusion of new datasets, which goes well beyond existing frameworks for archiving datasets. DANS facilitates the deposition of complete datasets, or static archives, with the capacity for a limited number of iterative updates and where each iteration is assigned an individual DOI. This situation appears overly reliant upon models for digital archiving of written text and ignores the dynamic opportunities that a more active archive can bring to researchers. The benefits of digital data repositories, whether static or active, allow information to become openly available and accessible, creating opportunities for re-use of that dataset in subsequent research. Perhaps as a result of the DOI attribution system, there is as yet no potential to create a digital resource that can be continuously updated, such as a repository/archive that has the ability to accommodate the research input of multiple teams/sources working towards a shared research goal. For this reason, TPW will deposit material into a research archive with DANS as a *static* archive in early 2021, as part of their Small Data Project incentive scheme. But in “an ideal data lifecycle”, as Kansa Whitcher and Kansa (2014, p. 225) put it, an archive should not be a “final resting place” for data. Indeed, the authors believe a dynamic archive, one in which resources are updated as new research is undertaken, is an important part of communicating and contextualising research. By increasing opportunities for research collaboration, both present and future, the TPW project better fulfils its societal impact goals and moves closer to building new knowledge about the innovation of the potter’s wheel. Therefore, the web portal to the *active* repository with a sophisticated back end will be hosted and maintained by the University of Amsterdam, enabling continued knowledge exchange between peers and the public.

8.5 Knowledge Transfer and Learning Pathways

An important component of the TPW Knowledge Hub which was identified early in the design process is the integration of learning pathways to facilitate knowledge transfer (for more information about the concept of learning pathways, see Hilditch et al. 2021). With the knowledge that potting technology assessment is a growing field which all too often depends on extended periods of in-person object study, TPW sought to create solutions which could widen participation. Furthermore, many digital archives are designed for use by well-experienced users who have deep pre-existing knowledge of the field, which excludes participation by students or the general public. The solution pursued by TPW is the creation of resources to orient users in terms of how to use the archive, as well as how to perform data collection and analytical tasks presented within the archive: in effect, facilitating non-specialists into becoming partially specialised users.

Tutorials and other kinds of learning tools guide users through the database, which are tailored to their level: specialist, student or general public. These tutorials not only inform on topics such as how to use the archive or a structured light scanner, but also allows knowledge transfer relating to a number of topics including recognising wheel-forming traces, new insights in ancient technology, the role of 3D visualisation in archaeological practice, and 3D models of heritage objects for the mobilisation of knowledge transfer. The reference collection of wheel-forming traces is the visual portal where the investigation of potting technology begins. A trained specialist can readily dive into the details by browsing further through the displayed contextual items, or by a targeted search. At all times, video tutorials and explanatory blog posts are easily accessible to help guide the user from superficial to complex exploration through the data. Students, as well as the general public, can start with the visual representations in the main view port. These may either be detailed photos of fabrics and vessels obtained by targeted light photography (for which the metadata scheme and how-to DIY manual is also available) or 3D models (for which workflow tutorials and metadata schemes are available). Both photos and 3D models are tagged so that the forming traces are recognisable, and these tags contain links to further explanations. A multitude of different file formats of the 3D models are made available to download, and a dedicated part of the reference collection has models of single macrotraces that can be downloaded for 3D printing. This unique training set enables users to tangibly explore traces of forming techniques, as a tactile survey of the surface is an essential part in the process of identifying forming techniques that cannot be replaced entirely by virtual technology.

The clear research objective-directed database risks the creation of so-called ‘filter bubbles’ which affect data retrieval and use through the application of particular search tools, and especially impact the structure of the data (Huggett 2020, S12). The easy access and functionality ideally democratise the use and re-use of data that could contribute to new knowledge and shaping narratives, but the simplicity of these tools inevitably channel this shaping in a certain direction. However, as long as this risk is acknowledged, and transparency about research aims is maintained, this directional shaping is not necessarily an un-democratic approach. Project data was collected for wider communication of past technological changes, as well as how to recognise features indicative of those technologies. The archive also provides recording strategies that maximises reproducibility and ensure comparability between datasets. In this respect, a fluid and flexible re-assembling and re-use of data in an unguided and 'free' way could lead indeed to interesting new interpretations by 'local stakeholders' and third parties, but whether this truly produces new scientific knowledge is debatable.

8.6 Summary

Some challenges and solutions for presenting and curating 3D data alongside other types of archaeological data have been briefly introduced here. The 3D models captured by TPW form an integrated part of the multiple datasets represented by diverse media and file formats presented within the database. Overall, the web-based archive democratises interaction with archaeological knowledge by opening access to specialised archaeologists, students, and non-specialists alike.

The question remains, however: how can we establish a sustainable repository that actively fosters further research by future users? 3D models are exceptionally useful as a means to simulate and stimulate intensive object study in the field or lab, a point which is reinforced by thoughtful creation of storage and access solutions. The TPW project has ensured that its datasets have met the basic requirements of sustainable archiving, such as catering for data quantity and format, open access, and adequate infrastructure for long-term storage. However, these basic requirements, which many other projects are also currently meeting, do not necessarily foster strong interaction by users. On top of this, the commercial platform Sketchfab is dependent upon an economic profit model, whereas 3DHOP requires the continued investment of the Italian state and the European research framework, risking accessibility of the 3D models in the long term. Lastly, 3D models remain at present a volatile format, in which their accuracy relies upon the standards of ever-changing current technologies. Taking all these uncertainties into account, it is imperative that the contextual data making the 3D model meaningful should be stable, sustainable, and accessible at all times. For now, TPW seeks to exceed the requirements within existing data frameworks by depositing our data with the Dutch national digital data repository DANS, and by listing the objects on Europeana soon afterward.

The TPW team sought to push beyond balancing between stability and usability by supplementing the deposition of datasets with a custom-built, user-friendly web-based database, and has forged a strategy where integrated data management meets known project objectives (see Fig. 8.5). The TPW Knowledge Hub will promote learning processes for recognising wheel traces, and provide structured 'on boarding' or familiarisation for data collection techniques through manuals, learning pathways and guidelines.

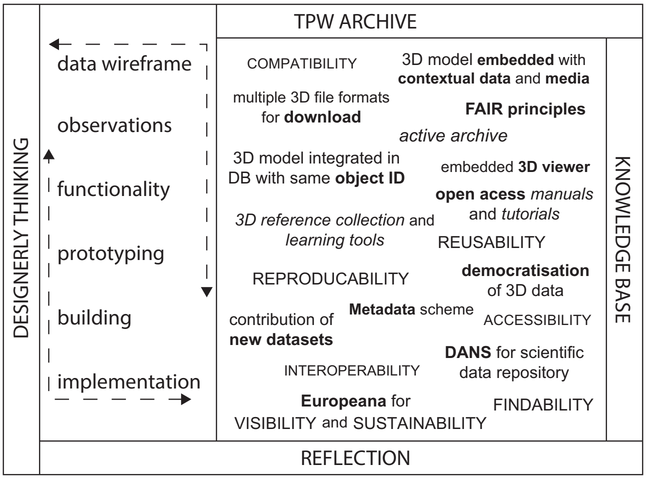

Fig. 8.5 Summary of TPW's workflow, *outputs*, **primary aspects** and GOALS in creating the active archive. (Image: L. Opgenhaffen)

8.7 Future Directions

One of the project aims has been to stimulate research into how potter's wheel technology spread across the Aegean over time. A remaining, major task now is to advocate for others to make use of, and ultimately contribute to, this Knowledge Hub. This involves training other specialists to recognise and interpret evidence for pottery production technology, as well as encouraging gathering of further data on this topic. Potential users of the Hub can be reached by presenting in specialist sessions on digital (3D) pottery archives, but widening engagement with general users must also be achieved through other means, such as interactive museum exhibits and online activities. By using a simple embedded viewer with integrated features alongside the wider contextual information of TPW datasets, and enabling multiple download files, the 3D reference collection has a special role to play in helping users to transition into the role of a specialist in an interactive and even tactile way.

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References

1D Icons Ireland. http://www.3dicons.ie. Accessed 15 Sept 2020

ADS metadata scheme. Guidelines for Depositors. In: ADS Archaeology Data Service. Available via ADS. https://archaeologydataservice.ac.uk/advice/Downloads.xhtml. Accessed 15 Sept 2020

ArchAIDE. The ArchAIDE project. http://www.archaide.eu. Accessed 14 Sept 2020

ARKEOTEK. The Arkeotek Journal. http://www.thearkeotekjournal.org. Accessed 18 Sept 2020

Beazley Archive. Classical Art Research Centre. https://www.beazley.ox.ac.uk/archive/default.htm. Accessed 14 Sept 2020

Boast R, Biehl PF (2011) Archaeological knowledge production and dissemination in the digital age. In: Kansa E, Kansa Whitcher S, Watrall E (eds) Archaeology 2.0: new approaches to communication and collaboration. Library of Congress Cataloging-in-Publication Data, Los Angeles, pp 119–158. http://www.escholarship.org/uc/item/1r6137tb

Börjesson LI, Huvila I (2018) Digital archaeological data for future knowledge-making. In: Huvila I (ed) Archaeology and archaeological information in the digital society. Routledge, New York, pp 1–13

Champion E, Rahaman H (2020) Survey of 3D digital heritage repositories and platforms. https://doi.org/10.4995/var.2020.13226

CHARM. CHARM Cultural Heritage Abstract Reference Model. http://www.charminfo.org/Overview.aspx. Accessed 14 Sept 2020

CIDOC CRM. Conceptual Reference Model. http://www.cidoc-crm.org/functional-units. Accessed 12 Sept 2020

Cinema Parisien. http://vondel.humanities.uva.nl/cinema/export_unity_5.3.3.html. Accessed 16 Sept 2020

Clarke RI (2019) Design thinking. ALA Neal-Schuman, Chicago

CRANE Project. The Computational Research on the Ancient Near East project (CRANE). https://www.crane.utoronto.ca. Accessed 13 Sept 2020

Dallas C (2015) Curating archaeological knowledge in the digital continuum: from practice to infrastructure. Open Archaeol 1(1). https://doi.org/10.1515/opar-2015-0011

DANS Dutch Data Archiving and Networking Service. https://dans.knaw.nl/en. Accessed 5 Sept 2020

Dorst K (2011) The core of 'design thinking' and its application. Des Stud 32(6):521–532. https://doi.org/10.1016/j.destud.2011.07.006

Dynamic Collections. https://www.darklab.lu.se/digital-collections/dynamic-collections/. Accessed 15 Dec 2021

Ekengren F, Callieri M, Dininno D, Berggren Å, Macheridis S, Dell'Unto N (2021) Dynamic Collections: a 3D web infrastructure for artifact engagement. Open Archaeol 7(1):337–352. https://doi.org/10.1515/opar-2020-0139

Gardin J-C, Roux V (2004) The Arkeotekproject: a european network of knowledge bases in the archaeology of techniques. Archeologia e Calcolatori 15:25–40

GRAVITATE-EU. Geometric Reconstruction And noVelsemantIcreunificaTion of culturAlheriTageobjEcts. http://gravitate-project.eu. Accessed 13 Sept 2020 (site no longer up)

Hilditch J, Jeffra CD, Opgenhaffen L (2021) The tracing the potter' s wheel project (TPW): an integrated archaeological investigation of the potter' s wheel in the bronze age Aegean. IANSA XII(2). http://iansa.eu/papers/IANSA-2021-02-tracing-the-potters-wheel-project_onlinefirst.pdf:345–355

Huggett J (2020) Is big digital data different? Towards a new archaeological paradigm. J Field Archaeol 45(sup1):S8–S17. https://doi.org/10.1080/00934690.2020.1713281

Ideo Design Thinking. https://designthinking.ideo.com. Accessed 12 Sept 2020

Jeffra C (2011) Contenus. In: Collections de la technothèque. Available via PréTech. https://teknotek.pretech.cnrs.fr/s/fr/item?fulltext_search=Jeffra&fbclid=IwAR0_gKMvjcCKee2qOggmdww8I-Pk4RFszHSRPW5bOq7p1zkr8eOeeoKLPCE. Accessed 19 Sept 2020

Johansson-Sköldberg U, Woodilla J, Çetinkaya M (2013) Design thinking: past, present and possible futures. Creat Innov Manag 22(2):121–146. https://doi.org/10.1111/caim.12023

Kansa Whitcher S, Kansa E (2014) Data publishing and Archaeology's information ecosystem. Near Eastern Archaeol 77(3):223–227. https://doi.org/10.5615/neareastarch.77.3.0223

Levantine Ceramics Project. The Levantine Ceramics Project (LCP). https://www.levantineceramics.org. Accessed 14 Sept 2020

Noordegraaf J, Opgenhaffen L, Bakker N (2016) Cinema Parisien 3D: 3D visualisation as a tool for the history of cinemagoing. Alphaville: J Film Screen Media 11:45–61

Norman DA (2013) The design of everyday things. Revised and Expanded edn. The MIT Press, Cambridge/London.

Opgenhaffen L (2020a) TPW workflow series: post-processing 3D scans. Available via Tracing the Wheel. https://tracingthewheel.eu/tpw-workflow-series-post-processing-3d-scans. Accessed 28 Sept 2020

Opgenhaffen L (2020b) TPW workflow series: democratising 3D data. Recording the process of 3D scanning and processing. https://tracingthewheeleu/article/tpw-workflow-series-democratising-3d-data-recording-the-process-of-3d-scanning-and-processing. Accessed 28 Sept 2020

Piotrowski M (2019) Acceptingand Modeling Uncertainty. Die Modellierung des Zweifels – Schlüsselideen und -konzepte zur graphbasierten Modellierung von Unsicherheiten 4. https://doi.org/10.17175/sb004_006a

PréTech. Préhistoire et Technologie. UMR 7055. http://www.pretech.cnrs.fr/programmes-labex. Accessed 28 Sept 2020

Rowe J, Razdan A, Collins D, Panchanathan S (2002) Digital library system: capture, analysis, query, and display 3D data. In: Marchionini G, Hersch W (eds) Proceedings of the ACM International Conference on Digital Libraries. Portland, p 382. https://asu.pure.elsevier.com/en/publications/digital-library-system-capture-analysis-query-and-display-3d-data. Accessed 12 Dec 2019

Sarwar A, Fraser PT (2019) Explanations in DesignThinking: new directions for an obfuscated field. She Ji: J Design Econ Innov 5(4):343–355. https://doi.org/10.1016/j.sheji.2019.11.002

Smith N, Karasik A, Narayanan T, Olson E, Smilansky U, Levy T (2014) The pottery informatics query database: a new method for mathematic and quantitative analyses of large regional ceramic datasets. J Archaeol Method Theory 21(1):212–250. https://doi.org/10.1007/s10816-012-9148-1

Statham N (2019) Scientific rigour of online platforms for 3D visualization of heritage. Virtual Archaeol Rev 10(20):2019. https://doi.org/10.4995/var.2019.9715

The British Museum. The Britisch Museum Online Collection https://www.britishmuseum.org/collection. Accessed 17 Sept 2020

Wilkinson MD, Dumontier M, IjJ A, Appleton G, Axton M, Baak A et al (2016) The FAIR guiding principles for scientific data management and stewardship. Sci Data 3(1):160018. https://doi.org/10.1038/sdata.2016.18

Chapter 9
Sharing and Caring for the Bioarchaeological Heritage: What Should We Do With 3D Data in the Post-acquisition Stage?

Jugoslav Pendić, Jelena Jovanović, Jelena Marković, and Sofija Stefanović

Abstract This paper discusses ways of collecting, storing and sharing 3D datasets of large archaeological assemblages, taking as a case study the Lepenski Vir anthropological collection. Several hundred human bones from individuals dated to Mesolithic-Neolithic have been digitalised through the use of image-based modelling, as well as volumetric and dedicated 3D scanners. The project was centred on providing undisturbed and meaningful options for accessing 3D scans of normally restrictively available physical samples, as well as establishing a base ground for further use of digital output. The results have been presented through the 3DHOP environment, providing a proxy to geometry and texture information, as well as contextual information about the finds. The authors elaborate on the workflow and storing strategies, as well as the possibilities for the public to interact with the digital catalogue. The paper also takes note of sensitivity of the digital 3D content created on the basis of archaeological record – and specifically human remains – for the process of online sharing.

Keywords 3DHOP · LepenskiVir · Volumetric scanning · Neolithisation · Photogrammetry

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9.1 Introduction

Lepenski Vir represents one of the most important sites for studying the process of Neolithisation in Europe and it is the eponym site of the local Mesolithic–Neolithic culture. Its position (in the north-central Balkans, on the border between Romania and Serbia, the Danube Gorges form a natural passage between south-eastern and central Europe), temporal continuity (Mesolithic–Neolithic occupation, ca. 9500–5500 calBC), the richness of its material culture (trapezoidal dwellings, raw material, ornaments, sculpted boulders, etc.) and human skeletal remains (>200) provides a unique contextual framework for examining the nature and dynamics of the Neolithic expansion, as well as the adaptation of the farming way of life to new natural and social environments.

Over the past decades, our knowledge about the life and the origins of the inhabitants of Lepenski Vir has greatly expanded. Intensive human occupation of this site started during the tenth millennium BC, suggesting that local Mesolithic hunter-fisher-gatherers (9500–6200 calBC) adopted a sedentary way of life prior to and independently of animal and plant husbandry, before the sixth millennium BC (Borić 2011; Dimitrijević et al. 2016). The stable isotope analysis and zooarchaeological record suggests that the Mesolithic diet was based primarily on the consumption of fish (freshwater and anadromous species) and hunted games(Dimitrijević et al. 2016; Živaljević 2017; Jovanović et al. 2019). During this period, we witness the appearance of dogs which were domesticated locally (Dimitrijević and Vuković 2015).

Radiocarbon dating models indicate a rapid expansion of the Neolithic in the Central Balkans at the end of the seventh millennium BC and confirm the pattern of population growth in the centuries following the spread of the first farming communities (Blagojević et al. 2017; de Becdelièvre 2020; Porčić et al. 2021). During this time (c. 6200–5950 calBC, Transformation/Early Neolithic period), intensive contacts between the inhabitants of Lepenski Vir and Early Neolithic communities from the neighbouring regions have been documented. This is apparent from the presence of new material elements characteristic of the Early Neolithic Stračevo culture at Lepenski Vir, including ceramics, polished stone axes, Balkan flint and shell beads made from Spondylus (Borić 2011). Moreover, unique artistic creations and architectural developments (anthropo-zoomorphic sculpted boulders, sophisticated trapezoidal buildings) also appear in the archaeological record. Elements of both continuity and novelty have also been observed in the mortuary repertoire during this period, such as Mesolithic-like supine positions and the practice of burying children under red-plastered floors of the buildings, pointing to the Southern Balkan and Anatolian Neolithic sphere (Borić and Stefanović 2004). Data from ancient DNA (Hofmanová 2016; Mathieson et al. 2018) and strontium radiogenic signals (Borić and Price 2013) indicate that at this time migrants came to Lepenski Vir who were genetically closer to individuals found at Early Neolithic sites in Anatolia. Palaeogenomic studies have also shown that local individuals with European-Mesolithic-like ancestry mixed with the newcomers from Anatolia (Hofmanová 2016; Mathieson et al. 2018; de Becdelièvre et al. 2020).

After 6000 BC, further important socio-cultural changes occurred at Lepenski Vir and this phase is marked as Early/Middle Neolithic period, c. 5950–5500 calBC. This period is characterised by the abandonment of the trapezoidal houses, the appearance of new type of domestic structures, domesticated animals (i.e., cattle, pig, goat and sheep) and inhumations in a flexed position, which are typical of Anatolian and European Early Neolithic communities (Borić 2013). Although domesticated animals appeared, stable isotope and zooarchaeological studies show that their consumption remained subsidiary to fish and wild game (Borić and Dimitrijević 2007; Dimitrijević 2008; Živaljević 2017; Jovanović et al. 2019). While most of the descendants of the local foragers continued to perpetuate their dietary traditions, the descendants of the migrants mostly adopted local fishing practices (de Becdelièvre et al. 2020). With regard to crops, a recent study suggests that some individuals dated to the Transformation/Early Neolithic and Early/Middle Neolithic phases may have consumed domesticated cereals (Filipović et al. 2017; Jovanović et al. 2021).

Although various elements of Neolithic culture arrived at Lepenski Vir, many studies showed that the transition from Mesolithic fisher-hunter-gatherers to Neolithic early pottery users was neither straightforward nor sudden, since many Mesolithic cultural traditions were still very much alive during the Neolithic. From a bioarchaeological perspective, this can be seen primarily in the continuity of the local economy, as well as mortuary practices that paint a picture of complex cultural syncretism at the onset of the Neolithic. Thus, Lepenski Vir gives valuable insights into the interactions between foragers and farmers along the Danube, in addition to highlighting the role of the social and ecological landscape that shaped the development of farming niches which may have subsequently further influenced the process of Neolithisation in the Balkans and Europe.

The 3D-scanning project was carried out by the combined effort of the Laboratory for Bioarchaeology, Faculty of Philosophy, University of Belgrade (http://bioarchlab.org/rs. Accessed 17 Jan 2021) and the Center for Biosystems, BioSense Institute, University of Novi Sad (https://biosens.rs/?page_id=12564&lang=en. Accessed 17 Jan 2021). So far, over 250 individual bones from grave contexts at Lepenski Vir and sites within the Danube Gorge have been scanned using multiple techniques. Image-based modelling was the main method of digitalisation used, followed by micro-computerised tomography (μCT) and computerised tomography (CT). The structured light scanner was least utilised, with access to the instrument being outsourced. For image-based modelling, Reality Capture was the chosen solution, the micro-computerised tomography was provided by BruknerSkyscan 1275 model and the dedicated structural light scanner unit was Range Vision: Spectrum. A medical CT scanner data,, was outsourced from a private medical laboratory (Fig. 9.1).

Two aspects should be singled out. First, neither of the research units involved allocated resources exclusively for 3D digitalisation, nor was this their primary work activity. Second, the acquisition of data was by and large completed within the relatively short time frame of two months of non-continuous scanning, with additional forays conducted on later occasions, mainly focused on μCT acquisition. The

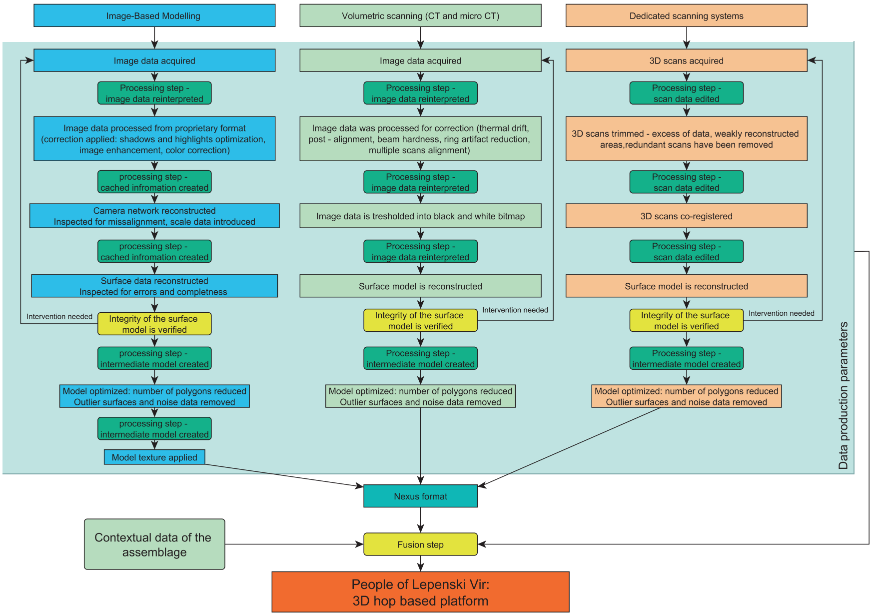

Fig. 9.1 The graph of the pipeline used for creating the 3D collection of Lepenski Vir

selection of samples included representatives of different age and sex groups, but the 3D scanning was not limited to diagnostic or impact-laden parts of the body. Rather, it covered every individual part that would be accounted for in a bioarchaeological record, regardless of size and fragmentation. Bias towards better preserved and more easily interpreted parts (by the public or by experts) would not have aligned with the idea of systematic coverage of the assemblage.

9.2 Sampling Strategy

The choice of remains to be entrusted to the 3D-scanning procedure was a multi-tier decision. At the core of the selection model are the questions driving the need to create digital replicas. We define them here as a group of major enquiries, followed by a set of secondary research questions to be resolved by the time the project is completed:

Is it possible to effectively share 3D content across a multitude of platforms with users who have varying levels of experience in dealing with 3D environments? The assumption is that a collection of 3D models can be distributed with context and paradata, in addition to geometric and (where applicable) colour information, while at the same time largely (but not completely) negating issues such as refresh rate

(Molloy and Milić 2018), format interoperability and Level-of-Detail (LOD) thresholds.

In the knowledge that digital copies of human remains can be made accurate and with high levels of conformity to their physical counterparts, the project was interested in the prospect of treating the 3D-scanning deliverable as a tool for further studies. What is the procedure for making instruments out of 3D scans that can be used for comparative morphometric studies across the assemblage(s) and additive manufacturing?

The choice was thus guided by the need to represent all major sex and age categories, skeletal division groups and skeletal parts, with a particular focus on cranial skeletons (cranial skeleton examples, both complete and partially preserved, constitute nearly one-fifth of the digital replicas, however this is due to pronounced fragmentation of infant cranium bones). In addition, the presence of bone modification (i.e. disease-induced modification, traumatic events and slow processes) was identified as a trait to be fostered in the sample.

Secondary enquiries to be addressed by 3D scanning on the assemblage level include:

- How does a 3D scan fare as substitute to physical access to an anthropological sample?
- The assumption is that existence of a 3D collection of human remains from an (eponymous) archaeological site, would inspire engagement with the digital replicas on the part of students, researchers and the public, potentially reducing handling stress on actual (human) remains.
- Can the collection of 3D datasets covering a massive sample be conducted in the same dynamic way as any other classical form of archaeological documentation activity? The assumption is that, despite apparent logistical issues and unknowns (e.g. storing strategies, estimated speed of data production, lack of established standards), the 3D scanning of an assemblage of hundreds of ‘objects’ is a feasible secondary activity for a research unit with no primary interest in exclusive production of 3D content (just like any other type of documentation, such as image files or drawings of finds, that are created by mixed research teams).
- The greater the number of individual scans, the more prevalent issues relating to the storage and curation of progenitor data become. What should be kept for further use and what should discarded?

9.3 Providing 3D Models at a Large Scale

From the perspective of a craftsperson (as defined by Dolfini and Collins 2018), the process of 3D scanning can be made extremely elaborate. The number and position of scan stations, scanning or image loops around the artefact, exposure, overlap, speed or distance from the surface of interest can be varied experimentally, potentially leading to substantial improvements. However, there is not always time for such experiments for each object, as the issue is not just one of quality, but of quantity too. If there is more than one object, there will be more than one shape or material or both, and there will also be a timetable to be followed.

The author's assumption was that dynamic development of software and hardware will make any detailed how-to guidelines covering each step obsolete or irrelevant, potentially after only a season or two, and there is thus little value in inscribing them in stone. More importance was attached to the means by which available instruments work with samples and to establishing general rules. For example, we found that the anthropological material handled contains fine details, which are faithfully reproduced in images and provide a multitude of features that can be recognised in the camera-network reconstruction stage of image-based modelling (Table 9.1). We also found that software can be guided to use fewer, but more accurately selected tie points (resulting in an overall better-quality model). In the case of volumetric scanning (Table 9.2), it was found that human teeth are particularly prone to the formation of ring artefacts (Boas and Fleischmann 2012) in the datasets and that this can effectively be eliminated by enabling random movement of the stage during acquisition. Moreover, even thin bones can be well documented by means of a structured light scanner (Table 9.3), with an increasing number of rotation steps during scanning, providing enough overlap between partially observed surfaces to successfully carry out the mutual co-registration stage. These (amicably designated) 'hacks' are signs of an emerging familiarity of the craftsperson with the material, and are quite similar to learning processes observed in standard methods of archaeological documentation.

The technical pipeline manual was determined by means of a series of test trials and feedback between technician staff (with little or no training in anthropology) and anthropologists (with limited or non-existent experience of 3D scanning) as end users. This was done repeatedly for each source of datasets (i.e. image-based, volumetric and dedicated scanning systems), creating a general set of outlines that can be referred to each time a problem arises within the process. This would ultimately provide a highly detailed and accurate 3D reconstruction of the human remains from Lepenski Vir for each geometry source.

Once completed, 3D models were deployed through an open-source environment designed with the representation of cultural heritage in mind. The 3DHOP (Potenziani et al. 2015), produced by the Visual Computing Lab in Pisa, boasts well-stocked technical documentation that keeps pace with the setup phases (https://3dhop.net/. Accessed 17 Jan 2021). Included within the same environment are tools that are helpful for engaging with the assemblage, i.e. tools for the acquisition of metrical data, the orthographic projection of principal axial views, the enhancement of geometry characteristics via projected light and the possibility to create sections and isolate particular parts of the model (Fig. 9.2). The workflow forces a levelling of the playing field, converting diversified sources of 3D geometry into a single data-structure option. The stipulated format, multiresolution .nxs (.nxz), has no interoperability with industry-standard software, as it is pigeonholed into a single working domain. This makes it a prospective solution that allows for

Table 9.1 Data source – image-based modelling system of people of Lepenski Vir

Image-based reconstruction system			
Entry no.	Attribute description	Setting	Comment
1	Image format	DX (crop sensor)	N/A
2	Acquisition conditions	Controlled environmental light	Flash lightning and textureless, uniform background, rotary table
3	Camera stabilisation	Consumer-grade tripod	N/A
4	Image pixel resolution	24 MP	No downsampling in pre-ingestion stage
5	Image acquisition format	.nefRAW format	Acquired as 14-bit RAW format
6	Image processing	Colour correction, chromatic aberration removal, dynamic range adjustment, image masking, format conversion.	No cropping, no lens distortion correction or irreversible edits of images.
8	Geometry resolving software	Commercial solution with functions of data scaling and high control over reconstruction parameters.	No open structure; black-box nature of the program. Limited reporting available for each model.
9	Reconstruction of camera network	Image number per model ranging from 150 to 999 images. No image downsampling.	Maximum preselector features per image: up to 80,000 Maximum preselector features (tie points): up to 40,000 Est.maximumpixelerror: 1 pix
10	Scale introduction	Physical scale introduced through image dataset	Laboratory calibrated distances between scale markers for greater accuracy used wherever possible.
11	Reconstruction of geometry	Image downsampled for a factor of 2 for depth map calculation.	N/A
12	Model editing	Correction of non-manifold geometry, hole closing, model optimisation.	No interventions affecting surface integrity pertaining to physical characteristics of the bone sample (no localised smoothing or re-modelling)
13	Model format	.obj (with or without 4096/8192 texture tiles)	N/A

homogenous data structure, but at a hefty price of apparently losing advanced analytical potential available through other software. The strengths of 3DHOP and its standard are the ability to load and effectively display extremely high numbers of polygons, meaning that only the limits in consumption of storage space on the hosting structure determine the detail in which the 3D model can be shown.

Each model was connected with a metadata spreadsheet. Attributes included are: information about the site and context, responsibility (i.e. the author of the data collection and the quality-verification personnel), the method used, the metrics of the acquired data (i.e. the image number for the image-based modelling and the scan

Table 9.2 Data source – Micro CT system for people of Lepenski Vir

Volumetric scanning			
Entry no.	Attribute description	Setting	Comment
1	Instrument model	Micro CT scanner with flat panel detector and fast acquisition times.	N/A
2	Voltage and current	70–72 kV, 125 uA	Relative to particular sample and filter introduced. The listed setting is for Al filter active (used for majority of samples).
3	Pixel size	Between 5 and 30 μm, depending on the sample physical size	Imposed by the shape and size of the sample.
4	Filter	No filter or Al 1 mm filter	In accordance with sample structure.
5	Image averaging	4–8 frames	Determined by the thickness and density of the sample, for each sample.
6	Acquired scan angles	No full 360 degrees scan employed.	N/A
7	Rotation step	Between 0.1 and 0.2 degrees, depending on the sample shape.	Determined by the irregularity of the sample shape (i.e. samples prominently extruded on one axis required reduced rotation step)
8	Image resolution	Maximum obtainable resolution (no binning)	Est. 1944 × 1474
9	Image format	Tagged Image File Format (.tiff)	16 bit
10	Image processing	Correction of thermal drift, misalignment, beam hardening and ring artefacts, multipart alignment. Conversion to .bmp	N/A
11	Reconstruction of geometry	Maximum image resolution (no downsampling factor used).	N/A
12	Model editing	Removal of non-manifold geometry. Global smoothing of the model.	N/A
13	Model format	.stl	N/A

number for dedicated scanning systems), the osteoarchaeological information (i.e. age, sex, skeletal division, skeletal part, particular bone), dating and publication reference (Fig. 9.3).

3DHOP largely removes the visual appeal of a 3D scan out from the equation. The options for dramatisation of the digital content are limited, strictly focused on the dynamic lighting of the scenery; here we use dramatisation as a synonym for Physically Based Rendering (PBR), the photorealistic rendering of 3D content, or introducing emission, controlled transparency handles and the like. Whereas services such as Sketchfab excel at introducing multiple texture maps to increase the realistic look of the model or improving the model's interaction with the digital

Table 9.3 Data origins – Structured light scanner for People of LepenskiVir

Dedicated structured light scanner			
Entry no.	Attribute description	Setting	Comment
1	Instrument model	Close-range structured light scanner (entry to mid-level user)	N/A
2	Working distance	Minimum product declared distance	At a minimum, 0.3 m away from the object.
3	Texture capturing	Integrated cameras	Exposure and colour correction applied for each object.
4	Geometry acquisition	Partial FOV scans, taken at predefined step numbers.	N/A
5	Scan co-registration	Automatic, through proprietary software provided by the manufacturer.	Process assisted by manually deleting conflicting or background regions from partial scans.
6	Model editing	Surface mode provided in maximum LOD of the scanner.	N/A
7	Model format	.obj	N/A

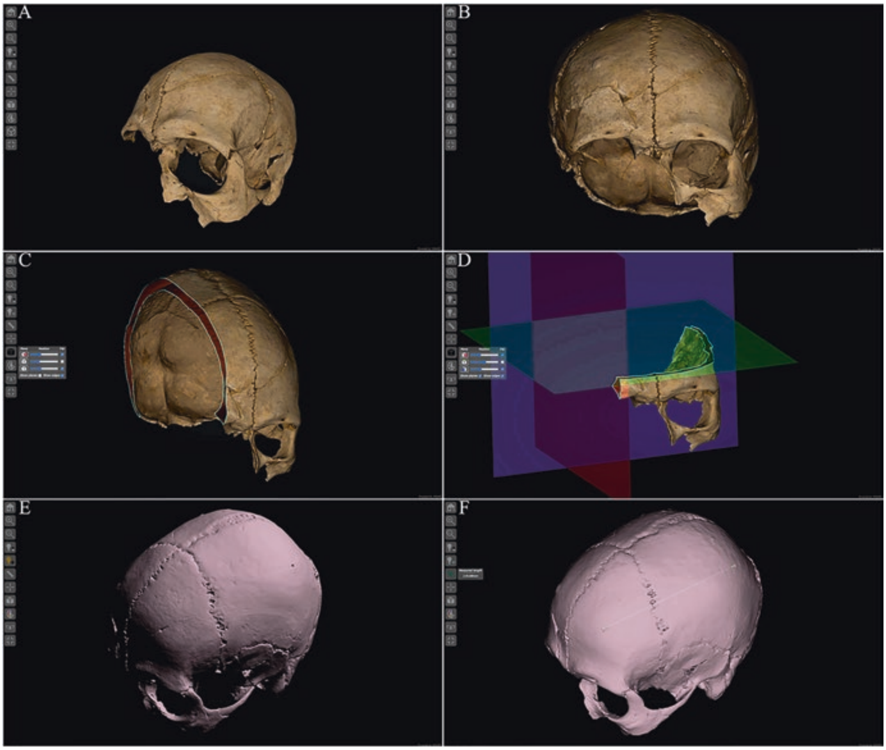

Fig. 9.2 (**a**) standard visualisation of the model, (**b**) ortho-projection, (**c**) cross-section, (**d**) isolation of the part of the model by cross-section planes, (**e**) responsive lighting conditions for enhancing surface detail, (**f**) measurement tool at work

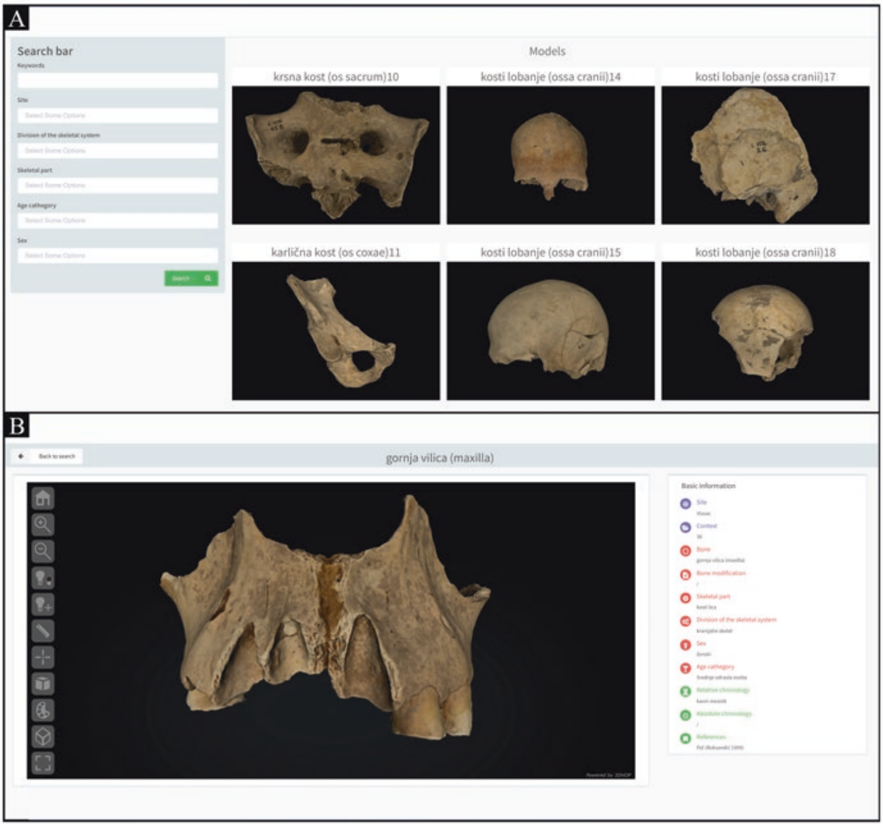

Fig. 9.3 (**a**) workbench of the catalogue with 3D models listed to the right and a search engine to the left, enabling visitor to browse by keyword, site, skeletal division, skeletal part, age category and sex of the individual, (**b**) workbench screen of an individual 3D object

environment and the public, 3DHOP relies on a spartan, function-driven design. This is not a shortcoming, but it does emphasise the innate expectations that archaeological finds could (should?) be striking to look at.

9.4 The 3D Collection of Lepenski Vir

People of Lepenski Vir (https://3d.biosense.rs/3DPortal/#/app-h/dashboard. Accessed 17 Jan 2021) is an online repository that provides limited access to the original files in the collection: there is no option to download either of the models made and a portion of the metadata is concealed from the visitor. The latter restriction was implemented to prevent the user panel from becoming overloaded with information that is not bioarchaeological (paradata related to the digitalisation process is not disclosed, but is viewable by an administrator). Admittedly, restricting direct access to the model stands in stark contrast to the democratisation brought about by the 3D-scanning process: the message delivered is that everyone can do a 3D scan, but there is no problem if only a few can review the product from bottom to top. The authors had relied on the online environment of 3DHOP to deliver options for assessing quality and context, but deliberately omitted the potential for reuse, since it was unclear what the afterlife of the generated models would be if these were fully downloadable. One could evoke the list of industries that use 3D scanning (e.g. interior and exterior design, gaming, product placement, etc.) and suggest that most users would be liable to find a secondary purpose for a 3D model coming from an archaeological assemblage. Moreover, ethical issues would not be far behind. While I do not believe that making Lepenski Vir models freely downloadable would invite the massive and uncontrolled repurposing of the assemblage, there should be a comprehensive environment that protects all involved: creators, content and stakeholders. It was proposed that the feasibility of open access to 3D-scanned human remains is governed by two factors: the temporal gap and the culturally sensitive nature of the material. Recent human remains are more liable to be withheld from public access (and even more so those originating from modern conflicts), while those of ancient origin, especially of high importance to the research community, are easier to distribute. The cultural sensitivity of the local living communities, as important stakeholders who claim the ownership over displayed and managed objects, represents the second factor (Ulguim 2018). Concerns about the misuse of the digital osteoarchaeological record from Lepenski Vir arise from both perspectives, as a rather intimate connection with the country's population is established *through* the great age and scientific importance of the assemblage. Lepenski Vir is strongly present in the publicly constructed archaeological landscape of the Republic of Serbia, as only a handful of other monuments of (archaeological) cultural property exist. It is also a target for a number of pseudo-archaeological agendas, often driven by misplaced sensationalism (Milosavljević and Palavestra 2017) and a desire to find ever older roots for the nation in the ancient past.

Furthermore, the local legislative framework recognises human remains of ancient populations as the cultural property of the state, and the 3D models of the remains are loosely viewed as documentation pertaining to the original find, and thus, broadly interpreted, as taking on characteristics of the cultural property itself. Hence, facilitating full access to the models, while imposing a strict view on ownership and licensing, without the tools to claim and protect these asserted rights in the digital environment would likely not give the desired result.

That said, none of the above considerations outweighs the benefits of direct reuse of 3D models to foster engagement between the community and bioarchaeological assemblages, or a re-evaluation of the material through research activities. What 3D documented archaeological object excels at is the sheer number of new reinterpretations which it enables: a 3D model can be enhanced, with regard to both geometry and colour information, materialised beyond the basic metrics into a tool for direct comparison, or introduced into a digital environment for immersive handling.

From this perspective, the tools provided with the Lepenski Vir catalogue are limited, but point ahead to the next level of development. An overhaul of the catalogue would ideally include the possibility to download a progenitor 3D object (not the nexus standard) and increased contextualisation through the introduction of engagement handles on the model that provide detailed information about points of interest. Such features would serve to prevent the 3D model from being relegated to the role of a mere showcase and allow it to be more actively used. Notably, the introduction of persistent identifiers for each 3D object would allow for direct referencing (Ulguim 2018), provided that the digital repository is a stable source of data flow for a longer period. A prerequisite for this would be the formulation of a clearer legal framework for dealing with 3D models of cultural heritage.

The project explored the option of creating instruments from 3D scans to facilitate further uses, beyond the inclusive access to digital content, for purposes related to morphometric comparative studies and additive manufacture. Data complexity was identified as one of the primary bottlenecks impeding effective manipulation of scanned human remains. Detail-heavy models are also massive datasets, and in virtue of the composition of collection, models are units belonging to a multi-part system: an arm, leg, pelvis, shoulder, chest or cranial group of bones, which, in turn, can be made to work together in the digital realm. Whereas the 3DHOP partially handles the issue of casual/fast browsing of the 3D content in a way similar to browsing images on a hard drive, there is an interest in introducing direct model-to-model shape and volume comparison. This interest has been also expressed by researchers outside the project staff, following the first presentation of the Lepenski Vir 3D collection in EAA Bern 2019. No viable solution for this in 3DHOP architecture has so far been devised for the Lepenski Vir project: a separate piece of software, such as Cloud Compare or Meshlab, can be used externally, but the procedure can be burdened by surface mesh density, available hardware and user familiarity with the software. It also requires direct access to progenitor 3D models. In order to facilitate the comparative potential in an assemblage, uniform scale needs to be imposed on the data. The volumetric and dedicated scanners used achieve this through calibration at the pre-scan stage, but image-based modelling require that the scenery contains points with known distances, preferably with only minute errors in dimensions. Colour information can be made uniform across the sample by colour checkers, however this aspect can vary between acquisition platforms (image-based modelling/dedicated scanners), as well as between models, where light-source distance and resolving power can affect the exposure and acquired dynamic range of images (image-based modelling).

When it comes to additive manufacture, the geometrical integrity of the models is paramount. Printing human remains requires that the appearances of objects without thickness, disconnected vertices and edges, internal faces, etc. (commonly known as non-manifold geometry) be removed from the surface model. These may appear at multiple stages, as the result of decimation of the model, closing gaps in the object surface or straight from the software/hardware used to acquire data. Once again, optimisation of the models is an important factor: an overly detailed model will still be printed within the limits of the printer's technical capacity, but excessive complexity (which will anyways be omitted from printed replicas) may cause hold-ups in laying out the printing procedure. The orientation of the digital model is also of importance for certain printing procedures – polylactic filaments (PLA) are layered prints, and the orientation of the layers (printing position of the object) may affect rendering of surface features.

Assessments of 3D scans – regardless of whether they are presented through a 3DHOP environment or third-party software – as a suitable replacement for direct access to the physical object revealed overlaps between experiences. The reported loss of synchronisation in working with a digital copy was noticed, referring to 3D model manipulation and coordinate systems of the 3D model (what is right and left, up and down, and how to facilitate desired orientation), as well as limited depersonalisation of handling and separation between the physical and digital. The latter term refers to the reported notion that the digital version is a completely new object and that repeated visits to the physical sample were needed to establish a connection with it. However, the surface and (where available) internal features of the remains – notably trauma- and disease-induced changes (for comparison download access to partial or complete 3D models was made here, here and here) – translate well into a new environment and are identifiable and accountable, with clear morphometric traits. It is, however, still unclear whether the disparity in experience is removed after prolonged exposure to the dataset working domain.

The Lepenski Vir project has provided a convincing argument that 3D scanning can be performed in the background of other research activities at a physical anthropology laboratory (or indeed any other functional research unit). Whereas volumetric model creation is limited to inducted and certified technicians, other close-range 3D scanning techniques are taught and upgraded by stable and continuous submission to the process, even for users with no background in any form of digitalisation. Of special note is that the applicant should be encouraged to engage in experimental forays, as these actively build a sense for the potential of the heritage 3D content and the capacity to manage and analyse it (thus reducing the chances that this content will sit out its time on a backdrop hard drive). Unsurprisingly, however, the speed achieved does not compare to the speed with which more classical forms of archaeological documentation are created. The People of Lepenski Vir project has shown that, in one working shift, the raw data needed to make a complete 3D model can be created for up to 10 samples from the collection. When processing was taken into account, however, our numbers went down to 3–5 fully completed samples per day. Furthermore, given the fact that 3D models are **not** able to provide instant information, but rather require additional efforts, tackling a body of finds without access to a streamlined workflow can result in a protracted entanglement, where information and effort is piled up, but no quality feedback or deliverables are produced.

This brings us to the last issue, concerning the storage of raw and intermediate products. The People of Lepenski Vir project preserved the core products and outputs, discarding most of the transitional steps between the two. This is exemplified by all three data sources, in which dependencies, offshoot products and temporary datasets were made, which were not vital to the continued life of the project or individual scan. Arguably, there could be benefits to being able to respond quickly and retrace one's steps to a particular moment in the workflow. However, the general sentiment on the Lepenski Vir project was that this would not be an optimal investment of time and resources. Instead, a record was kept of how models were generated, from the acquisition stage to the final output. This largely conformed with the point 7 of the 'Basic Principles and Tips for 3D Digitisation of Cultural Heritage' (https://ec.europa.eu/digital-single-market/en/news/basic-principles-and-tips-3d-digitisation-cultural-heritage#2.%20Select%20what%20to%20digitise. Accessed 20 Jan 2021). We expect that the processing software will continue to make major jumps and that old datasets can be revisited if the opportunity arises to obtain improved results.

The online catalogue represents a decent step forward in helping make the bioarchaeological assemblage of Lepenski Vir accessible to observers. It appears that the community of researchers concerned with 3D documentation and content in archaeology and cultural heritage has reached at a stage where both the curation and distribution of 3D is branching out through experiments with reliable and widely compatible solutions to achieve both goals (Erolin et al. 2017; Fanini et al. 2019). While it seems that this is leading to the formation of individual clusters of context-specific collections, important work is being done and the availability of the 3D output, for both the general and expert public, is improving steadily, ultimately moving towards formalisation.

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References

Blagojević T, Porčić M, Penezić K, Stefanović S (2017) Early Neolithic population dynamics in Eastern Balkans and the Great Hungarian Plain. Documenta Praehistorica 44:18–33. https://doi.org/10.5281/zenodo.1218367

Boas FE, Fleischmann D (2012) CT artifacts: causes and reduction techniques. Imaging Med 4:229–240

Borić D (2011) Adaptations and transformations of the Danube gorges foragers (c. 13,000–5500 cal. BC): an overview. In: Krauß R (ed) Beginnings – new research in the appearance of the Neolithic between Northwest Anatolia and the Carpathian Basin. Papers of the international workshop 8th–9th April 2009, Istanbul. Verlag Marie Leidorf GmbH, Rahden/Westf, pp 157–203

Borić D (2013) Lepenski Vir: geography and culture. In: Smith C (ed) Encyclopedia of global archaeology. Springer, New York, pp 4494–4502

Borić D, Dimitrijević V (2007) When did the 'Neolithic package' reach Lepenski Vir? Radiometric and faunal evidence. Documenta Praehistorica 34:53–71. https://doi.org/10.4312/dp.34.5

Borić D, Price TD (2013) Strontium isotopes document greater human mobility at the start of the Balkan Neolithic. Proc Natl Acad Sci 110:3298–3303. https://doi.org/10.1073/pnas.1211474110

Borić D, Stefanović S (2004) Birth and death: infant burials from Vlasac and Lepenski Vir. Antiquity 78:526–546. https://doi.org/10.1017/S0003598X00113201

de Becdelièvre C (2020) Ecology and ethology of human populations living in the Danube Gorges ca. 9500–5500 BC. Bioarchaeological perspectives on dietary behaviors and adaptive strategies during the Mesolithic and Neolithic transformations. PhD thesis, University of Belgrade

de Becdelièvre C, Jovanović J, Hofmanová Z et al (2020) Direct insight into dietary adaptation and the individual experience of Neolithization: comparing subsistence, provenance and ancestry of Early Neolithic humans from the Danube Gorges, c. 6200–5500. cal BC. In: Gron KJ, Sørensen L, Rowley-Conwy P (eds) Farmers at the frontier: a pan European perspective on Neolithisation. Oxford/Philadelphia, Oxbow Books, pp 45–76

Dimitrijević V (2008) Lepenski Vir animal bones: what was left in the houses? In: Bonsall C, Boroneant V, Radovanović I (eds) The iron gates in prehistory. New perspectives. Archaeopress, Oxford, pp 117–130

Dimitrijević V, Vuković S (2015) Was the dog locally domesticated in the Danube Gorges? Morphometric study of dog cranial remains from four Mesolithic–Early Neolithic archaeological sites by comparison with contemporary wolves. Int J Osteoarchaeol 25:1–30. https://doi.org/10.1002/oa.2260

Dimitrijević V, Živaljević I, Stefanović S (2016) Becoming sedentary? The seasonality of food resource exploitation in the Mesolithic–Neolithic Danube Gorges. Documenta Praehistorica 43:103–122. https://doi.org/10.4312/dp.43.4

Dolfini A, Collins R (2018) Modelling physical and digital replication: bridging the gap between experimentation and experience. Open Archaeology 4:36–49. https://doi.org/10.1515/opar-2018-0002

Erolin C, Jarron M, Csetenyi LJ (2017) Zoology 3D: creating a digital collection of specimens from the D'Arcy Thompson Zoology Museum. Digit Appl Archaeol Cultural Herit 7:51–55. https://doi.org/10.1016/j.daach.2017.11.002

Fanini B, Pescarin S, Palombini A (2019) A cloud-based architecture for processing and dissemination of 3D landscapes online. Digit Appl Archaeol Cultural Herit 14:e00100. https://doi.org/10.1016/j.daach.2019.e00100

Filipović D, Jovanović J, Rančić D (2017) In search of plants in the diet of Mesolithic–Neolithic communities in the Iron Gates. In: Mărgărit M, Boroneanț A (eds) From hunter-gatherers to farmers: human adaptations at the end of the Pleistocene and the first part of the Holocene. Cetatea de Sacun, Târgoviște, pp 93–111

Hofmanová Z (2016) Palaeogenomic and biostatistical analysis of ancient DNA data from Mesolithic and Neolithic skeletal remains. PhD thesis, University of Mainz

Jovanović J, de Becdelièvre C, Stefanović S et al (2019) Last hunters–first farmers: new insight into subsistence strategies in the Central Balkans through multi-isotopic analysis. Archaeol Anthropol Sci 11:3279–3298. https://doi.org/10.1007/s12520-018-0744-1

Jovanović J, Power RC, De Becdelièvre C, Goude G, Stefanović S (2021) Microbotanical evidence for the spread of cereal use during the Mesolithic-Neolithic transition in the Southeastern Europe (Danube Gorges): data from dental calculus analysis. J Archaeol Sci 125:105288. https://doi.org/10.1016/j.jas.2020.105288

Mathieson I, Alpaslan-Roodenberg S, Posth C et al (2018) The genomic history of southeastern Europe. Nature 555:197–203. https://doi.org/10.1038/nature25778

Milosavljević M, Palavestra A (2017) Zloupotreba prirodnih nauka u (pseudo)arheologiji. Issues Ethnol Anthropol 12:825–851. https://doi.org/10.21301/eap.v12i3.8

Molloy B, Milić M (2018) Wonderful things? A consideration of 3D modelling of objects in material culture research. Open Archaeol 4:97–113. https://doi.org/10.1515/opar-2018-0006

Porčić M, Blagojević T, Pendić J, Stefanović S (2021) The Neolithic demographic transition in the Central Balkans: population dynamics reconstruction based on new radiocarbon evidence. Philos Trans R Soc B Biol Sci 376:20190712. https://doi.org/10.1098/rstb.2019.0712

Potenziani M, Callieri M, Dellepiane M et al (2015) 3DHOP: 3D Heritage Online Presenter. Comput Graph 52:129–141. https://doi.org/10.1016/j.cag.2015.07.001

Ulguim P (2018) Models and metadata: the ethics of sharing bioarchaeological 3D models online. Archaeologies 14:189–228. https://doi.org/10.1007/s11759-018-9346-x

Živaljević IRS (2017) Ribolov na Đerdapu u ranom holocenu (10.–6. milenijum pre n. e.). PhD thesis, University of Belgrade

Chapter 10
3D Content in Europeana: The Challenges of Providing Access

Kate Fernie

Abstract Europeana is an online platform that provides access to millions of items of digital content from Europe's museums, galleries, libraries, archives and research institutions. Although 3D documentation has become more common in recent years, the majority of the content accessible via Europeana comprises of images and text documents. This chapter describes the context and general challenges of making 3D content accessible online, and the specific challenges for Europeana. The creation of highly accurate 3D models of monuments, buildings and museum objects has become more widespread in research, conservation, management and to provide access to heritage for education and tourism. Yet this is still a developing field and organisations that are commissioning 3D media need to make a series of choices on the type of content that is created, how it will be visualised online and for which users. The challenges of storing and providing access to this content include the multiplicity of content types and formats, the technology requirements and limitations faced by different audiences, and issues such as low standardisation, the complexity and volumes of data involved, interoperability, and lack of metadata. Working collaboratively in developing standards for 3D content formats and metadata will increase interoperability, improve access, storage and preservation of 3D media.

Keywords 3D · Digital cultural heritage · Europeana

10.1 Introduction

Digitising cultural heritage to generate 3D models of objects, monuments, buildings and urban centres has become more common in recent years. Technologies for modelling the real world in 3D are being used in research, conservation, building

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management and by cultural institutions to democratise access and to reach new audiences for education, tourism and creativity. There are several aspects to this endeavour. Creating high quality representations of three-dimensional objects which capture their shape, colours and textures accurately, and rendering 3D content in a meaningful way are important. Another aspect, the focus of this article, is delivering 3D content over various platforms and operating systems in ways that are readily accessible to the general public.

10.2 Europeana

Europeana is Europe's digital cultural platform and allows users to search for cultural resources from institutions and organisations across Europe. Launched by the European Commission on 20 November 2008, Europeana currently provides access to over 58 million digital objects including art, music, sound, images of historic buildings and sites and a budding collection of 3D content.

Thousands of European archives, libraries and museums work with Europeana to bring their digital collections to users. The content is digitised and published online by the institutions on their websites who then share metadata descriptions of the content with Europeana in the standard Europeana Data Model (EDM) format. Working with tens of thousands of institutions means that standards, protocols and formats are fundamental to Europeana, which strives to offer end-users easy and immediate access to the content. For images and text files standardisation of formats and their support on the web means that Europeana's main focus is on encouraging institutions to publish high resolution content with a direct link to the files in their metadata, which allows users to view content discovered in Europeana on their devices (Scholz 2019). For audio, video and 3D content users need to be able to play the content to have a full experience, which means either publishing the content in formats that can be played in a web browser or delivering the content in a media player that is embeddable using standard protocols. But delivery is not the only challenge as the volume of data that is being served up (especially for video and 3D) means that the robustness and connectedness of the playout service are relevant factors in terms of the user experience.

10.3 3D Content in Europeana

In January 2019 a Europeana network association task force was established with the aim of increasing the support for 3D in Europeana and its availability for users. It is worth emphasising that Europeana works with a very broad range of institutions – from major national museums, libraries and research institutions to small site museums. There are experts in 3D digitisation in Europeana's network, but for many in the network 3D is still new. Organisations beginning 3D projects are making a series of choices about how the content is captured, visualised and made accessible to users. A relatively small number of 3D models had been made available via Europeana by the start of 2019. A review found this content offered users a variable user experience, with some 3D objects that could be interacted with online and models available for download not readily distinguished from simple images or videos of 3D content.

An important aim of the task force was to inform, support and encourage organisations which are creating 3D content, and to offer better guidance on the availability of more functional 3D content for Europeana's users to discover, explore and reuse.

10.4 Challenges of Providing Access to 3D Content Online

Until recently sharing 3D data over the internet was considered to be an unsolved need (Alliez et al. 2017). Various solutions existed but often required end users to install specific software on their computers to open the 3D file – either in the form of a browser plugin or a programme to be used to open a file download. The variety of software involved made this process inconvenient and annoying for users and represented a barrier to access. Why would a user download and install software simply to assess whether a 3D file was relevant and usable?

When providing access, a range of factors are important:

- The needs of different audiences
- The types of 3D content
- The technology requirements and limitations (of content and audience)
- The formats of 3D content
- Sharing 3D data over the internet.

10.4.1 Audiences for 3D

Knowing the audience is also important when providing access to 3D content. If we consider five categories of audience:

- Scholars and researchers creating and reusing 3D datasets in their research
- Educators and students using 3D content to meet learning objectives
- Museums creating virtual exhibitions and facilitating user engagement
- Professionals who are creating and using 3D datasets in their work
- General users

It is clear that each of these audiences has their own interests, needs and requirements from 3D. For example, researchers and professionals are more likely to require highly detailed, accurate 3D models that they can download and re-use in

Fig. 10.1 Recording the 3D structure of one the internal tombs at Knowth, BrúnaBóinne using a terrestrial laser scanner. (© The Discovery Programme)

their own projects (Fig. 10.1 illustrates the capture of such detail). Teachers may be looking for good quality models for 3D printing or for lightweight models that their students can explore online. There are a broad range of user scenarios with some audiences looking for well-presented content that tells a story, while others look for scientific content that is made available online in services that allow users to measure and compare objects. While file downloads work for some audiences, most users benefit from being offered access to a lightweight version of a 3D model with enough metadata to allow them to assess the qualities of heavier weight versions being offered for download.

10.4.2 Types of 3D Content

There is a broad range of different types of 3D content that may potentially be made accessible via Europeana. The main types include:

- Content generated from images and measurements of real-world cultural heritage objects, buildings, archaeological monuments and landscapes.
- 3D radiological imaging, magnetic resonance and Computerised Tomography (CT) scanning of objects such as mummies
- Visualisations and virtual reconstructions, which may be based on real-world measurements, modelling projects and academic research to visualise an object in its original context and setting
- Historic Buildings Information Models produced for buildings management
- 3D models produced for games, which use programming techniques to generate scenes and interactions as a player moves through the model
- 3D artworks which can range from animations depicting dances and the intangible heritage, to hyper-realistic drawings and models.

Archaeology is well represented among these content types. Each has its own characteristic workflow, which often involving specific equipment, standards and

Fig. 10.2 Saint Salvator abbey and landscape. (© Visual Dimensionbvba)

formats. Take for example the difference between scanning a biological object (such as a mummy or a skull) using medical imaging techniques and scanning a large historic building using 3D laser scanners. Or the difference between the methods and techniques used for recording an excavation of an archaeological site in 3D and those used to visualise a reconstruction of the site at a previous time (see for example Fig. 10.2). This is one of the reasons why capturing metadata about the process of creating 3D content is important. Metadata is as vital in understanding the quality and accuracy of what is depicted, as it is in helping users to discover 3D content.

10.4.3 Technology Requirements and Limitations

One of the factors that affects people's ability to access 3D content is the hardware, software and connectivity that is available to them. Different audiences operate in very different technical environments for example:

- Professionals/specialists have access to high-powered workstations equipped with specialist software and the processing power needed for highly detailed 3D models.
- Researchers may have access to high-powered computers in their labs but use different modes of access at home and different again in the field.
- General users are accessing 3D content via home computers with standard internet connections or by using on mobile devices.
- Educators and museum professionals generally access content via their organisation's network infrastructure using standard computers rather than high-powered workstations.

There can be other factors that restrict people's access to content, for example:

- Restrictions on software downloads. Many organisations restrict which software can be downloaded and installed on computers. But beyond this, when so much content opens and runs automatically within web browsers, users can be very reluctant to download and install software simply to view a file.
- Bandwidth. High resolution 3D content involves large volumes of data, which can be slow to access and/or download if users have weak network connections.

10.4.4 The Challenges of Interoperability, Usability and Sustainability

The range of different working environments and all this implies in terms of the methods, equipment and software that are being used in 3D projects means standardisation is at a relatively low level for 3D. Few standards are recognised by the International Organisation for Standardisation (ISO) (the Web 3D consortium's X3D standard and the Digital Imaging and Communications in Medicine DICOM standard are both ISO standards (Web3D Consortium n.d.; DICOM 2020)). There are some industry standards or common file formats (e.g. OBJ, PLY, DAE, STL and glTF) but many other proprietary formats are in use. Much 3D content is produced in formats that are specific to the software or equipment used.

This presents challenges for interoperability and usability from the perspective of both users and service providers. Users may find that they need to convert a file into a format that is supported by the software or service that they wish to use for their 3D project. Organisations developing services need to accommodate a lot of different file formats in use. A common approach adopted by organisations offering hosting services is converting files on import to a specified format. For example, Sketchfab supports conversion from more than 50 3D formats to the GL Transmission format (glTF) (Sketchfab n.d.). Software such as Blender provide routines for importing and exporting files in different formats. For end users, conversion to a common format can improve accessibility.

10.4.5 Sharing 3D Content Over the Internet

The number of different formats is related to the challenge of sharing 3D content over the internet. There are three main methods:

- Viewers
- File downloads
- Direct streaming

The early approaches to sharing 3D content on the web almost all required the installation of specific plugins on users' computers. In 2010, embedding 3D content in PDF documents offered a good solution to allow the broad public to view and interact with the content both online and offline (Pletinckx 2011). At that time the functionality needed for 3D was fully supported by Adobe and the content could be activated within most web browsers. But the potential for security vulnerabilities mean that autoplay of 3D in PDF is now disabled by default and use of 3D PDF has declined.

The introduction of HTML5 and WebGL brought about a revolution (Alliez et al. 2017). These days 3D content can be rendered directly on web pages. WebGL is the technology which allows Sketchfab (amongst others) to stream 3D content in real time to web browsers on a range of devices. 3DHOP, the 3D Heritage Online Presenter developed by CNR is another example of a software solution based on WebGL (Visual Computing Laboratory – ISTI – CNR 2020). 3D HOP allows high-resolution 3D datasets to be streamed efficiently and rendered for users. Available as an open-source download package, 3D HOP is available for installation by institutions (Potenziani et al. 2015). Potree is another example of open source software based on WebGl, in this case for rendering large point clouds (Schütz 2020).

WebGL is not the end of the story. Many museums and researchers are looking at 3D printing as a way of making their collections more accessible and for a range of purposes beyond education and outreach (Coates 2020). Once again specific methods, techniques and formats are involved. Projects and services such as "Scan the World" have emerged to make scans of archaeological objects, monuments and buildings available to download for printing (MyMiniFactory 2020).

The International Image Interoperability Framework (IIIF) is an important initiative that is bringing together institutions and individuals with an interest in 3D together to discuss interoperability and open standards. Building on previous work which defined a framework for delivering very high-quality images, text and audio-visual content, the IIIF 3D initiative has future potential to unlock access to 3D content that is currently locked in bespoke, locally build applications (IIIF 2020).

10.5 Challenges for Europeana in Providing Access to 3D Content

Cultural heritage institutions are increasingly thinking about 3D digitisation of sites and objects. A recent report for the European Commission highlighted increased funding by EU Member States for digitisation including monuments, historic buildings and archaeological sites in 3D (European Commission 2019). The fire at Notre Dame cathedral in April 2019 stimulated interest in 3D digitisation for conservation, preservation and providing online access (Veyrieras 2019). Initiatives such as 'Digital Syria' have also brought attention to the potential of 3D digitisation for preservation in conflict areas (Digital Syria 2019). Working with tens of thousands of institutions means that standards, protocols and formats are fundamental to

Europeana, which strives to offer end-users easy and immediate access to the content. More 3D content is being created, and more cultural heritage institutions are thinking about how to make this content accessible online.

10.5.1 Identifying Common Standards and Principles

For Europeana, which works with thousands of institutions, groups and individuals in making content available finding common ground is very important. Identifying principles and standards that are suitable for adoption by people who are creating 3D content in different contexts can only help address the challenges of delivery, access and longer-term preservation.

The final recommendations of the 3D Content in Europeana Task force (Fernie et al. 2019) included encouraging the adoption of a set of common file formats by Europeana data providers and aggregators, and in this way increasing interoperability, re-usability and longer-term preservation. The formats recommended were as follows: glTF, X3D, STL, OBJ, DAE, PLY and WRL plus DICOM (for radiography and computed tomography images) and IFC (for Building Information Modelling). This format recommendation was echoed in the basic principles published by the European Commission's expert group on Digitisation and Cultural Heritage and Europeana (European Commission 2020).

Narrowing the range of formats should begin to help with the next challenge, delivery.

10.5.2 Enabling 3D Delivery with Europeana's Platform

Europeana aggregates content that is hosted externally, usually in institutional repositories but sometimes on service platforms. A link within a Europeana metadata record directs users to the content which is made available:

- As a media file that can be viewed directly within an HTML page,
- Via a viewer that can be embedded within Europeana Collections, or
- Via an external web page

Some of the 3D media formats recommended can be rendered directly on an HTML5 web page, but much of the 3D content currently offered to Europeana is made accessible via viewers or media players.

In 2017 (Murphy and Europeana Foundation 2017) Europeana implemented the Sketchfab viewer within its platform. This development meant that cultural heritage institutions who, like the Discovery Programme, are uploading 3D models on Sketchfab (for example Fig. 10.3) could share the content with Europeana. Implementing the viewer meant that users were able to navigate the 3D content inside Europeana Collections for the first time.

Fig. 10.3 Newgrange. (© Discovery Programme: https://skfb.ly/DwQo)

As different viewers serve different audiences and use cases, the 3D content task force recommended that Europeana should extend its capabilities by seeking to embed additional 3D viewers such as 3D HOP and the Smithsonian Explorer (Fernie et al. 2019).

Work within the IIIF 3D community raises the possibility of developments in standards, APIs and viewers which support 3D and interoperability between 2D and 3D data.

10.5.3 Building Capacity, Adding New Content

Surveys of Europeana's network of data partners and work by the European Commission's expert group on Digitisation and Cultural Heritage and Europeana highlight the need to build capacity amongst cultural institutions. Whilst there is a lot of interest in 3D amongst museums and other cultural institutions, with the notable exception of archaeology and the built heritage, there is limited experience of 3D digitisation. Developing training for cultural heritage institutions is a good way of increasing the amount of good quality 3D content and metadata that is made available to Europeana.

10.6 Conclusions

Improving on the means of delivery for 3D and increasing standardization is currently very topical. The fire at Notre Dame highlighted the challenges of re-using 3D scans and models from past projects to create an integrated knowledge platform (Veyrieras 2019). Surveys of scholars in the field of Digital Cultural Heritage (e.g.

by the Friedrich-Schiller-Universität Jena in Germany) have identified 3D was an area of high demand concerning standardisation and policies. Work by Europeana's 3D content task force and the IIIF 3D community group highlight the interest from commercial, non-profit and academic sectors in developing 3D technologies and in standardization.

There is much potential and much work to be done before 3D content achieves the level of interoperability as still images with web platforms such as Europeana.

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References

Alliez P, Bergerot L, Bernard J-F, et al (2017) Digital 3D Objects in Art 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 Archeovision Lab. (France), November 30th – December 2nd, 2016. hal-01526713v2. Online. https://hal.inria.fr/hal-01526713v2

Coates C (2020) How are some of the world's best known Museums doing amazing things with 3D Printing? In: MuseumNext. https://www.museumnext.com/article/how-museums-are-using-3d-printing/. Accessed 16 Jan 2021

DICOM (2020) About DICOM: overview. In: DICOM. https://www.dicomstandard.org/about. Accessed 16 Jan 2021

Digital Syria (2019) The Digital Syria Initiative. https://digitalsyria.org.uk/. Accessed 16 Jan 2021

European Commission (2019) European Commission report on Cultural Heritage: Digitisation, Online Accessibility and Digital Preservation. https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=60045. Accessed 16 Jan 2021

European Commission (2020) Basic principles and tips for 3D digitisation of cultural heritage. In: Shaping Europe's digital future – European Commission. https://ec.europa.eu/digital-single-market/en/news/basic-principles-and-tips-3d-digitisation-cultural-heritage. Accessed 16 Jan 2021

Fernie K, Blümel I, Corns A, et al (2019) 3D content in Europeana task force. Europeana Network Association Members Council Task force report https://pro.europeana.eu/files/Europeana_Professional/Europeana_Network/Europeana_Network_Task_Forces/Final_reports/3D-TF-final%20report.pdf. Accessed 16 Jan 2021

IIIF (2020) IIIF 3D Community Group — IIIF | International Image Interoperability Framework. https://iiif.io/community/groups/3d/#about. Accessed 16 Jan 2021

Murphy A, Europeana Foundation (2017) Exploring 3D on Europeana with Sketchfab. In: Europeana. https://blog.europeana.eu/2017/01/exploring-3d-on-europeana-with-sketchfab/. Accessed 16 Jan 2021

MyMiniFactory, Scan the World (2020). https://www.myminifactory.com/category/scan-the-world. Accessed 16 Jan 2021

Pletinckx D (2011) Europeana and 3D. ISPRS – international archives of the photogrammetry. Remote Sens Spatial Infor Sci XXXVIII-5(W16):483–490. https://doi.org/10.5194/isprsarchives-XXXVIII-5-W16-483-2011

Potenziani M, Callieri M, Dellepiane M et al (2015) 3DHOP: 3D Heritage Online Presenter. Comput Graph 52:129–141. https://doi.org/10.1016/j.cag.2015.07.001

Scholz H (2019) Europeana Publishing Guide v1.8. https://pro.europeana.eu/files/Europeana_Professional/Publications/Europeana%20Publishing%20Guide%20v1.8.pdf. Accessed 16 Jan 2021

Schütz M (2020) Potree. https://github.com/potree/potree. Accessed 16 Jan 2021

Sketchfab (n.d.) Supported 3D File Formats – Sketchfab Help Center. https://help.sketchfab.com/hc/en-us/articles/202508396-Supported-3D-File-Formats. Accessed 16 Jan 2021

Veyrieras J-B (2019) A digital twin for Notre-Dame. In: CNRS News. https://news.cnrs.fr/articles/a-digital-twin-for-notre-dame. Accessed 16 Jan 2021

Visual Computing Laboratory – ISTI – CNR (2020) 3DHOP. https://3dhop.net/. Accessed 16 Jan 2021

Web3D Consortium What is X3D? (n.d.). https://www.web3d.org/x3d/what-x3d. Accessed 16 Jan 2021

Part V
Current Challenges and Future Perspectives

Chapter 11
Digital Archaeology Between Hype and Reality: The Results of a Survey on the Use of 3D Technologies in Archaeology

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Abstract Between January and March 2020, the EAA Community for 3D-Technologies in Archaeology conducted an international online survey on the current use of image-based 3D technologies. The aim was to gain broader insight into the application of image-based 3D technologies in archaeological practice and cultural-heritage management. The survey made it possible to determine the most important aims of the use of 3D technologies, as well as providing an overview both of the software and data formats used and of current archiving practices for raw and/or generated data. In this way, the main challenges for the further development of the techniques and the ongoing implementation of 3D technologies in practice can be identified.

Keywords Evaluating digital methodology · 3D documentation · Digital archaeology · Archiving digital data · Data processing

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11.1 Introduction

In the last decade, the use of 3D technologies in archaeology and cultural heritage has witnessed a progressive consolidation in most of its fields of activity. Nowadays, 3D techniques are a standard element in the archaeologist's toolkit. Moreover, these methods are not only used on site and in laboratories to document archaeological features and finds, but they have also proven their usefulness for tackling new research questions using 3D data (cf. Herzog and Lieberwirth 2016; Vollmer-König 2017; Howland 2018; Blaich et al. 2019; McCarthy et al. 2019; Pakkanen et al. 2020). Finally, 3D models also show great potential for use in public outreach and education (Hagenauer 2020; Unger et al. 2020).

However, the implementation of these techniques has not developed everywhere at the same pace or with the same goals and framework conditions. In some cases, these efforts started quite early, while in other cases they began only recently. The result is that many of the approaches remain individual (cf. Innerhofer et al. and Kruse/Schönenberger Chaps. 3 and 12 in this book, but also Winkler 2020). Thus, the landscape of 3D applications in archaeological practice is diverse and fragmented, and only recently have efforts been made to search for common ground at the international level (cf. the study VIGIE-2020-654 financed by the European Commission and hosted by the Digital Heritage Research Lab at Cyprus University of Technology: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=69940. Accessed 17 Jan 2021).

In order to acquire an overview of the various practical applications and individual strategies, an online survey was conducted between January and March 2020. The focus lay on questions concerning usage and archiving, as well as the professional environment of the participants. The survey was specially designed to cover the usage of image-based 3D technologies, because these are generally easy to incorporate into the pre-existing infrastructure of archaeological work environments, given that digital cameras and computer hardware are in most cases already accessible. Since the survey was designed as a pilot study into a relatively little-explored field of inquiry, it was kept quite broad, as were the possible answers. The target audience were archaeologists and other professionals from different working environments, such as institutional research (e.g. universities or academies), state monument offices (e.g. Landesdenkmalämter in Germany) and freelance archaeologists and technicians. There were no restrictions according to sub-discipline, meaning

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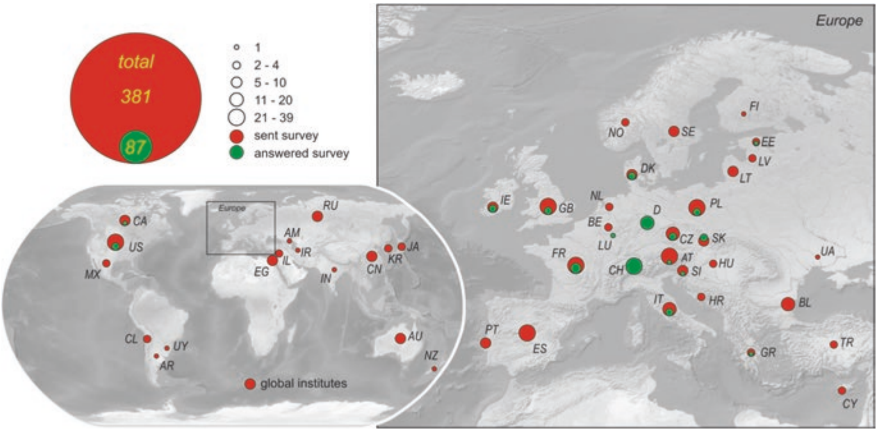

Fig. 11.1 Distribution and response to the survey

that the participants could have very different foci of expertise (e.g. numismatists, field archaeologists, Egyptologists, etc.) The survey was attached to 381 e-mails to institutions and individuals in 47 countries. It was also shared over social media (on Twitter and Facebook) and mailing lists. In total, 87 of the returned questionnaires were at least 80% complete (Fig. 11.1).

Even though the survey is not statistically representative, we were able to acquire an overview of the importance of 3D technologies with respect to their essential aspects, including the most important aims governing its general use, as well as the software, data formats and type of archiving employed. By means of these questions, we aimed to identify indicators of the challenges involved in the application of 3D technologies to archaeological practice. In the following chapters, we will present and discuss the results of the survey.

11.2 Results

11.2.1 Demographic Data

The survey reached a mainly European audience, with the majority of participants residing in Germany and Switzerland (Fig. 11.1). Over 70% of participants were male. In terms of age, 44% were 30–39 years old, 28% were 40–49 years old, 16% were 50–59 years old and only a few were older than 60 years. The participants mostly held positions within research institutions (i.e. universities, academies, etc.) or state monument offices. A portion of the participants worked as freelancers. The individual projects and positions were mainly connected to archaeology (in 80% of the cases).

11.2.2 Importance and Utilisation Objectives

In this section, participants were asked about their main objective in using 3D technologies, the usage context and how this task was allocated within their teams. The objective of this question was to assess the importance of 3D technologies for the participants, as well as the state of implementation in their working group or institution. For most participants, 3D technologies were of central importance to their projects, either as a means to an end (e.g. for documentation purposes) or as the main purpose of the project. When analysed according to field of work, participants at state monument offices and research facilities mostly considered 3D technologies to be a means to an end. Freelancers, by contrast, applied 3D technologies mostly in ‘particular situations’. Noteworthy were the numerous mentions of an ongoing test phase in all three fields of work (Fig. 11.2).

The important position occupied by 3D technologies was also reflected in the fact that one team member was usually responsible for the use of 3D technologies as a ‘specialist’. Only in the case of freelancers was it more common for a team member to deal with these technologies as an additional task (Fig. 11.3).

The most frequently mentioned goal for the use of 3D technologies was the documentation of excavations. This was followed by the targeted creation of 3D models for research, as products and, finally, for public outreach (Fig. 11.4).

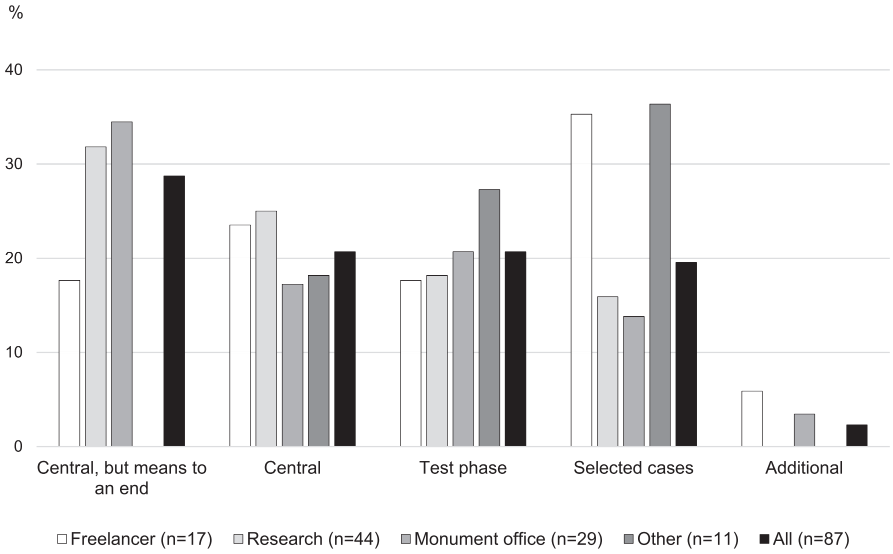

Fig. 11.2 The position of 3D technology in practice, broken down according to fields of work. Under ‘Other’ it was usually stated that the position varied according to the project

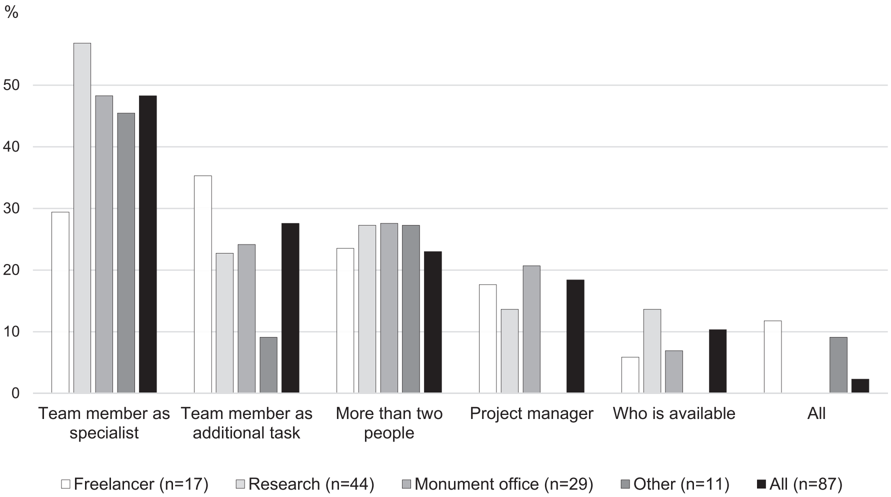

Fig. 11.3 'Who on the team works with 3D technologies?' The answers are sorted by the different fields of work

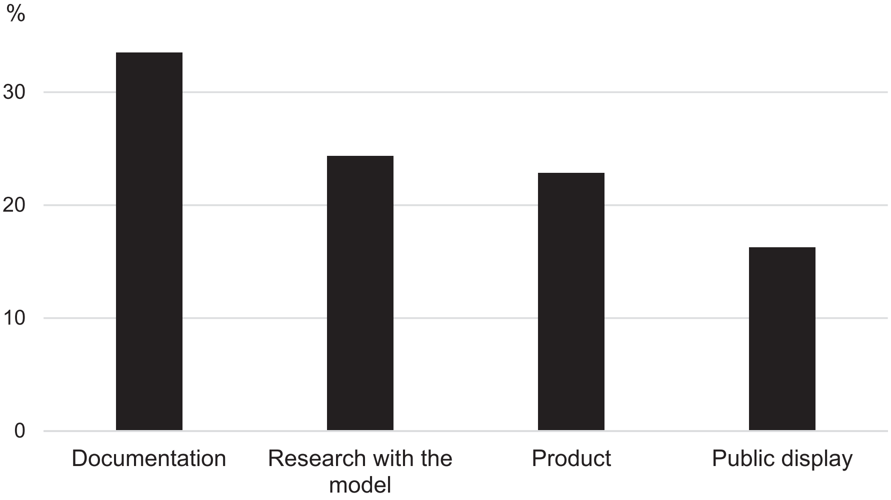

Fig. 11.4 Aims for the use of 3D technologies; 100% = 197

11.2.3 Software and Data Formats Used

This section of the questionnaire aimed at surveying the most common software applications and data formats used by the participants. In the questionnaire, seven software applications were listed as possible choices. There was also an option to

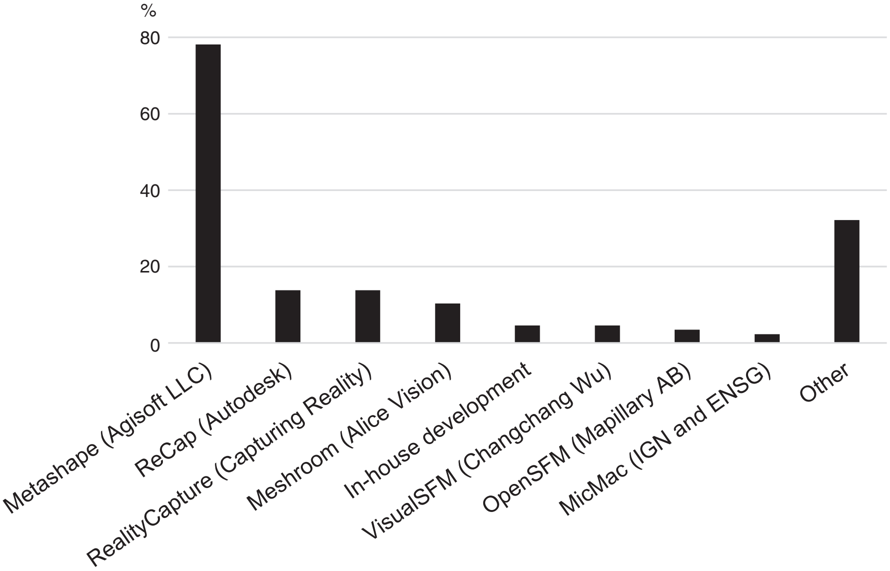

Fig. 11.5 Share of respondents who use specific software. Multiple answers were possible, which means that the sum of the percentage values is greater than 100; 100% = 87

indicate one's own developments or other alternatives, and multiple answers were possible (Fig. 11.5). In the answers, a total of 32 different software applications were listed, including 25 applications under 'other' (Table 11.1). The program Metashape by Agisoft LLC was by far the most frequently used. Other programs, such as ReCap Pro by Autodesk and RealityCapture by Capturing Reality, were named less frequently. Meshroom by AliceVision was the only open-source software mentioned in the top-four list and was used by 10% of the participants. The used applications can, for the most part, be categorised as 'complete solutions', which also include tools for georeferencing.

In order to query the frequency of the data formats used, a distinction was made between input and output data. By input data, we mean all data that is available before it is fed into processing software, while output data is the processed output, i.e. 3D models and digital elevation models, but also two-dimensional images, including, for example, orthophotos, unwrappings, profiles and the like. The boundary is to some extent vague and not absolute.

When it came to input formats, a limited, predefined selection of formats was offered, with the option to add additional formats. Multiple answers were allowed. Here, a similar picture emerged as in the case of software. A few formats were chosen most frequently (JPEG, TIFF and RAW formats, which were not further subdivided), but the total number of different formats was rather high (n = 21; Fig. 11.6).

In order to query the output formats, a predefined selection was given, with the option to mention additional formats. The results of the answers concerning output file formats are comparable to those for the input data, with only a few common

Table 11.1 Name (developer) and the number of mentions of the software solutions listed under 'Others'

Other Software Mentioned	Count
FARO SCENE (Faro Technologies)	3
MeshLab (Cignoni et al. 2008)	3
Artec Studio (Artec 3D)	2
Cinema 4D (Maxon)	2
CloudCompare (Daniel Girardeau-Montaut)	2
OptoCat (Breuckmann)	2
3DF Zephyr (3DFlow)	1
3DReshaper (Technodigit)	1
ArcGIS (ESRI)	1
Aspect 3D (Arctron 3D, Martin Scheuch)	1
Blender (The Blender Foundation)	1
CorelDRAW (Corel Corporation)	1
DEA (Digital Epigraphy and Archeology) (University of Florida)	1
GeomagicWrap (Artec 3D)	1
MODO (Foundry)	1
Pix4D (Pix4D SA)	1
Pointools (Bentley)	1
Rangevision Scan Center (RangeVision)	1
RiSCAN Pro (RIEGL – Laser Measurement Systems)	1
Robot Structural Analysis (Autodesk)	1
Scanstudio (NextEngine)	1
SketchUp (Trimble Navigation Ltd)	1
Unity3D (Unity Technologies)	1
V-Ray (Chaos Group)	1
ZBrush (Pixologic)	1

formats (Fig. 11.7). OBJ, JPEG and GeoTIFF were among the top-three formats, while a total of 20 different formats were mentioned. Of these, only OBJ can be considered a 'true' 3D file format. There seem to be hardly any differences between research institutions, state monument offices and freelancers.

11.2.4 Modalities of Archiving

The fourth section of the questionnaire focused on data management strategies and archiving practices. In order to assess this, it was asked whether guidelines were followed in the respective institutions or working environments. Participants were also asked about data formats for archiving, on the grounds that this might provide information about the awareness of challenges for long-term storage and interoperability. About half of the participants stated that there were institutional guidelines

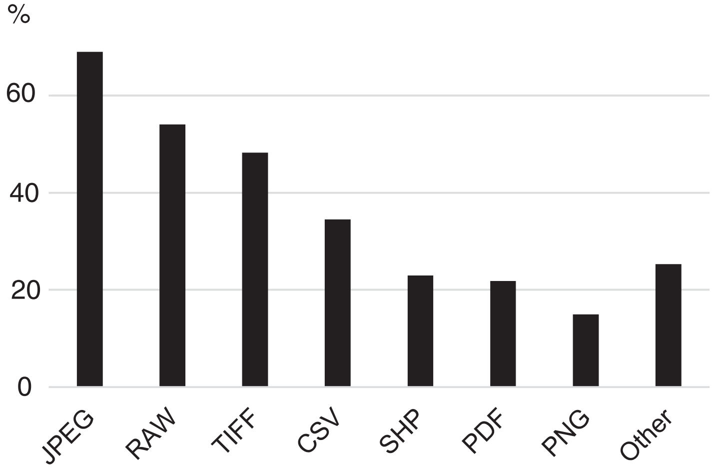

Fig. 11.6 Input data: share of participants who used a specific format. Multiple answers were possible; 100% = 87

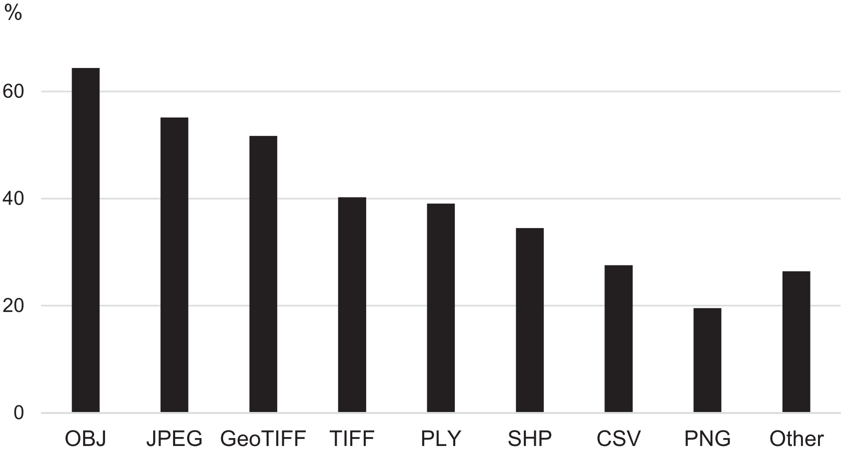

Fig. 11.7 Output data: share of the participants who use a specific format. Multiple answers were possible; 100% = 87

for archiving. From this, we can deduce that, in most cases, their approaches had been tested and validated, but that these approaches are presumably only rarely written down in the form of an established standard. Likewise, only about a quarter of the respondents had a data management plan or a comparable (recorded) strategy (Fig. 11.8). When broken down by fields of work, it was found that participants working in state monument offices and research institutes tended to have more formalised strategies than freelancers.

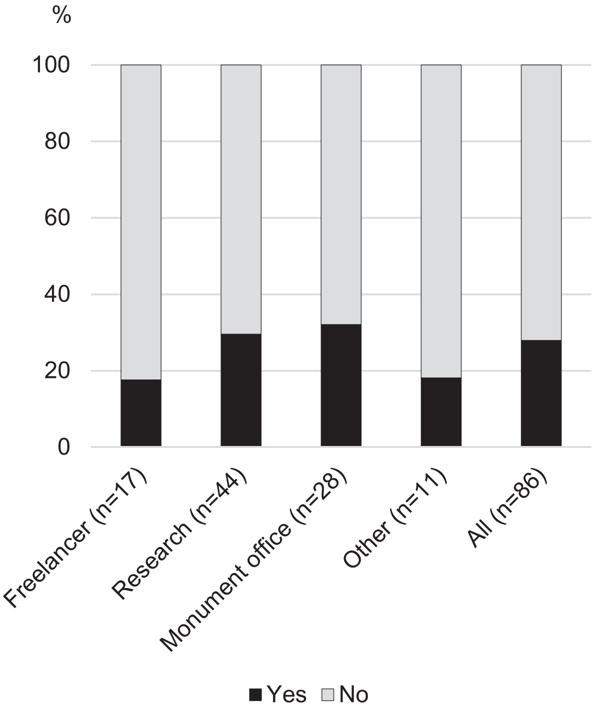

Fig. 11.8 Share of participants with or without a data management plan, broken down according to fields of work

Despite the paucity of fixed guidelines, respondents stated that they archived output data more often than input data (Fig. 11.9), with only slightly more than 20% of cases converting data (both input and output) into a specific archiving format. Only rarely was it stated that the associated software was archived as well.

The answers given concerning the file formats used for archiving input data revealed a preference for JPEG (around 60%) followed by RAW formats (55%) and TIFF (around 50%; multiple responses possible). When it came to archiving the output data, OBJ (55%), GeoTIFF (around 50%) and JPEG (around 40%; multiple answers) were listed most frequently. The available data storage capacity for archiving was mostly identified as lying beyond 1 TB, as in most cases this was identified as the required storage capacity. Here, the questionnaire was unable to solicit meaningful answers, as the question was too narrowly formulated. In addition to the input and output data, most participants stated that they stored the accompanying metadata, which is automatically generated, as well as additional metadata about the actual capturing process, such as the camera lenses and software packages used, and so on. However, multiple answers were not possible, obscuring the relationship between the answers. Most participants stated that the archiving method did not differ in virtue of the subsequent intended use of the datasets.

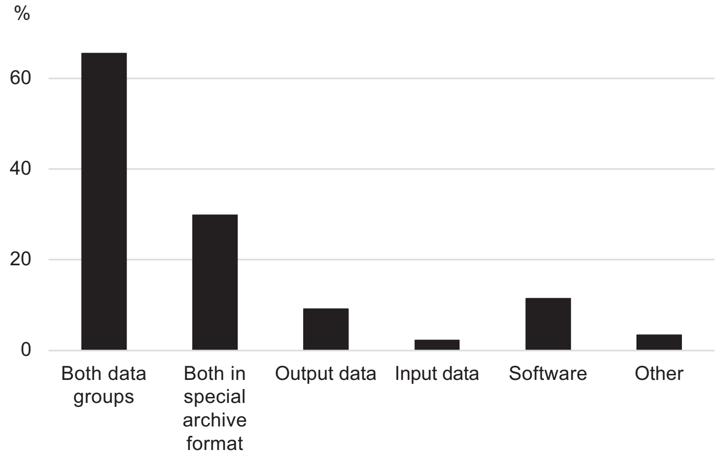

Fig. 11.9 Share of the participants who archived specific data formats. Multiple answers possible; 100% = 87

A lack of long-term experience with archiving digital data was repeatedly thematised in the responses. Nevertheless, confidence in the possibilities given was expressed by about 75% of the respondents.

With regard to the requirements for the archiving of 3D data, the participants most frequently identified the importance of the availability of sufficient storage capacities, high data security and secure protection. These answers were followed in frequency by the requirement of easy access and easy handling of the archives, as well as the ability to store the data on servers located in their own country with a long archiving timespan. The requirements that were accorded the least importance in the answers were the availability of support, public accessibility of the archives and version-dependent archiving (Fig. 11.10).

11.2.5 Accessibility of Data

Another important question concerned the accessibility of the data within the participants' working environment, which could provide information about who is authorised to access the data in a specific working environment. This might provide information about present risks and challenges. In the options given in the questionnaire, a distinction was made between an archive, where the data is stored and durably preserved without constant access, and a database, where the data is stored temporarily before or parallel to archiving but with constant access.

When asked about access authorisation, participants stated in most cases that the database was accessible only to team members. This was followed by in-house availability (Fig. 11.11). Public accessibility and restriction of access to individuals

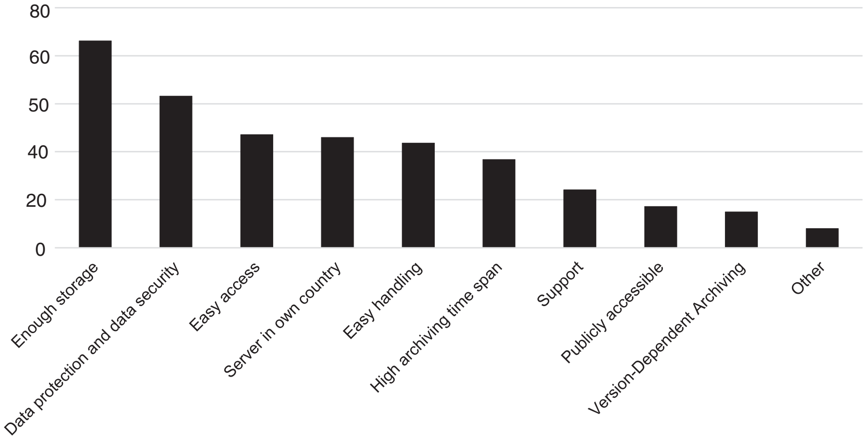

Fig. 11.10 Requirements for a digital archive for 3D data. Percent of participants for every answer

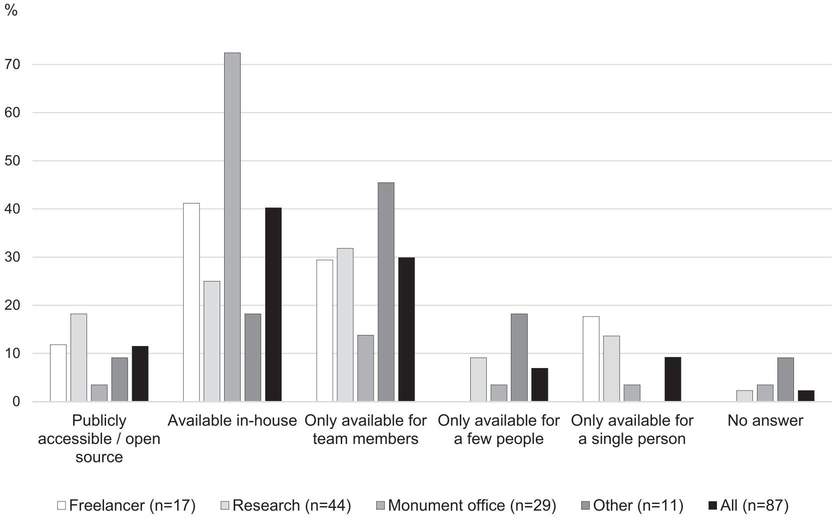

Fig. 11.11 Accessibility of the database containing 3D data

were only seldom mentioned. Public accessibility was mostly listed by participants working in (academic) research contexts.

The archives, by contrast, were mostly said to be accessible within the institutions. This was followed by being restricted to team members. It was relatively rarely claimed that access was restricted to specific individuals. Public access to archived data was also rarely listed, and when it was mentioned, it was mostly by participants working at research institutions (Fig. 11.12).

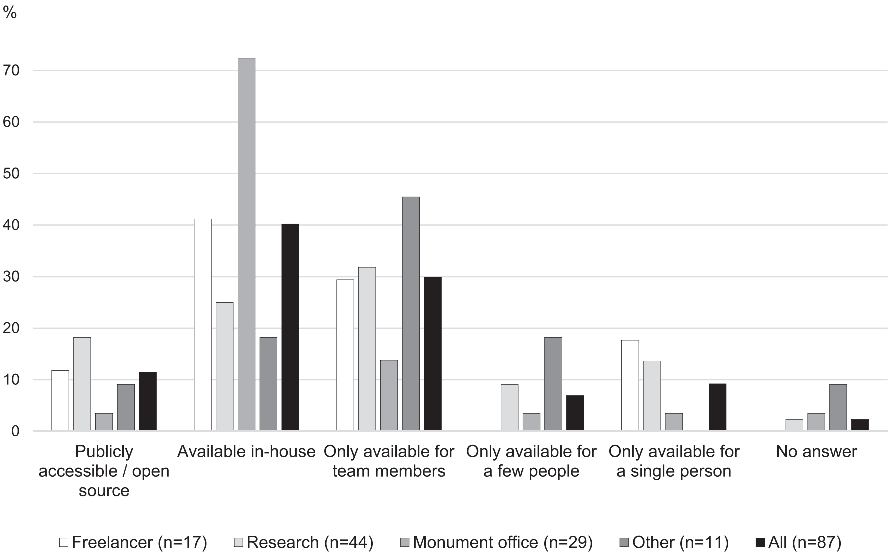

Fig. 11.12 Accessibility of the archive

11.2.6 Project Duration and Archiving Timeframe

For successful data management (independent of specifications or guidelines), both the project duration and the planned duration of archiving are important parameters. Both of these parameters were surveyed in the questionnaire, with predefined time ranges being given.

The most frequently stated project duration was five years (18%), followed by ‘less than six months’ (17%). Projects with a duration of three years came third (14%).

Freelancers stated that they worked mostly on short-term projects (less than one year, 43%) and on five-year projects (27%). Participants from research institutions mainly stated that they worked on projects with a duration of three or five years (20% and 24%), although projects with a duration of ten years also accounted for a significant share (16%). For participants working in state monument offices, a plurality of projects had a duration of less than one year (38%), while projects with a timeframe of more than 50 years were frequently listed as well (at a rate of 25%, as compared with about 11–13% for research institutions and freelancers).

The queried time horizons for archiving reveal two focal points, one at 10 years (28%) and the other at more than 50 years (33%). When these were sorted by field of work, it was revealed that freelancers and participants from research institutions, in particular, identified an archiving timeframe of 10 years or less (42% and 38%), while participants working in state monument offices stated that the archiving timeframe was generally more than 50 years (82%).

11.2.7 Guidelines?

The last section of the questionnaire asked whether guidelines would be supported, and solicited individual comments. The question of whether broad-based guidelines would receive support was largely answered in the affirmative (74%). The comments were diverse, but they all pointed in a similar direction: basic guidelines for the use of 3D technologies in archaeology could provide guidance, especially for less experienced colleagues. A second important point mentioned was the comparability and interoperability of the results that guidelines should aim to achieve. Reservations were expressed because many projects tend to have their own specific needs. It was therefore claimed that guidelines should be formulated in a sufficiently open manner, but without sacrificing their applicability.

11.3 Discussion

11.3.1 Demographic Data

The demographic questions were mainly asked in order to make it possible to group the participants in the evaluation of the survey. The focus lay mainly on determining the participant's broad field of work (i.e. academic context, state monument office or freelancer). Nevertheless, some other interesting observations could be made, giving potential insights into the structure of the field of archaeology.

For instance, the survey had a relatively low return rate from people over 60 years. This could be a sign of a generational shift in archaeology, as despite early pioneering applications of 3D technologies, the relevant techniques have only recently been used more widely. As the survey data indicates, 3D technologies seem to be more readily adopted by people aged 30–39 years, some of whom have been accustomed to the presence of digital technologies in their daily activities since childhood.

At the same time, a gender imbalance among the survey participants can be observed, with significantly more male respondents than female ones. Does this reflect an actual gender imbalance with regard to 3D technology or could other explanations be given? However that may be, it is important to keep in mind that the survey is not representative. One hint that the prejudice that it is mainly men who are interested in technology might not be correct is the large proportion of female authors in this book. As awareness about gender discrimination in archaeology is also currently increasing, this may deserve its own study.

11.3.2 Importance and Objectives of Use

A large proportion of the respondents viewed their use of 3D technologies as a means to an end, with high importance being assigned to the use of 3D technologies even in their daily work: 3D technologies are used in both the field and the laboratory for documentation purposes (means to an end), as well as for the study of specific questions (central role). For the respondents, 3D technologies are thus an important tool that is used routinely. However, this does not necessarily reflect the situation in the field of archaeology as a whole, since the survey explicitly targeted people with some sort of relationship to 3D technologies, with the result that it is unsurprising that 3D technology has significant importance for most of the participants.

More interesting is the relatively high percentage of participants who claimed to use 3D technologies in a testing phase (20%). Although the same limitation applies here, it nevertheless shows that the percentage of people entering the field may be rather large. This fits with the common picture of a growing interest in these technologies in recent years. Furthermore, it can be assumed that at least some of the respondents will soon integrate the technologies that are currently being tested into their regular practice. Accordingly, we can deduce the existence of a tendency towards further consolidation of 3D technologies in archaeological practice. The answers given to the question "Who in your team works with 3D technologies?" clearly show that tasks involving 3D techniques in archaeology are mostly carried out by specialised team members. This may be due to the fact that, until recently, academic training did not include the use of such techniques. The relevance of specialised team members for 3D documentation may also pose a risk in the context of fieldwork, as it is unclear whether other team members would be able to replace the specialist if needed. Giving a higher percentage of archaeologists training in 3D techniques as part of their basic education seems desirable.

11.3.3 Software and Data Formats

The evaluation of the questionnaire showed that there exist myriad different software applications and file formats. However, despite this large number of different options, only a few are used by a significant percentage of respondents. Although the survey is not representative, we assume that this observation (i.e. a few with high usage frequencies vs. a vast majority with low usage frequencies) may also be valid for the broader field.

When it comes to the choice to use a specific software application, it is probable that the decision is heavily influenced by the user-friendliness of the application, its flexibility in relation to different scenarios, and – in the context of archaeological documentation – the possibility of georeferencing the output. In our experience, Agisoft's Metashape meets all these criteria, which could be one of the reasons for its popularity. Another argument in favour of a certain product is its pricing. Autodesk ReCap Pro costs about €420 per year with a subscription and the permanent version of CapturingReality's Reality Capture costs regularly €15,000 (comparison of company websites). The 'Professional Edition' of AgisoftMetashape costs about $3500/€3000, while the 'educational license' for non-commercial purposes is priced at about $550/€470 (comparison of company websites). Archaeology and heritage management are usually not added-value-generating fields. The single-fee-based software applications seem preferable, as their cost is comparably lower. It can also be observed that commercial applications are mostly preferred over open-source solutions. From the perspective of open science and reproducibility, it would be preferable to have a broader application of open-source software in this field as well. However, this might change in the future, if open-source solutions are able to match the quality of their commercial competitors. The possibility of georeferencing, in particular, could potentially be a crucial development enabling open-source applications to become more useful for archaeological purposes.

Of all file formats, TIFF and JPEG are the most commonly used for 2D images. They have complementary characteristics, which makes them suitable for different purposes, and they have been in use for several decades, which probably gives them the best interoperability at present. In the case of RAW formats, which were often referenced as well, respondents retain the greatest-possible flexibility for recalculating images and thus accept a larger storage volume. However, RAW formats are mostly proprietary, which means that they cannot be considered an interoperable solution and face relatively early obsolescence.

OBJ and PLY are the most widely used 3D formats. Both enable the display of point clouds and polygon-based meshes. Aside from the possibility of calculating textures on the mesh and the linkage with other information, OBJ and PLY are accepted for import and export by most common software applications (Jones and Church 2020). Although GeoTIFF is a 2D raster, it can still be used as a digital elevation model (DEM) for three-dimensional research questions. In particular, the analysis and manipulation of extracted surface or terrain models within a Geographical Information System (GIS) is probably common practice.

Answers explicitly mentioning GIS or 3D GIS as tools were infrequent. However, this may be due to the fact that the questionnaire focused more on the acquisition of 3D data than on evaluation and post-acquisition use. At least one mention of ArcGIS was recorded, possibly indicating the use of 3D data in a GIS context. In the context of this survey, it remains unclear how extensively 3D GIS is used, as the questionnaire did not query the further examination and use of 3D outputs. However, in the past decade, the application of 3D GIS has been significantly developed (cf. Katsianis et al. 2008). Recently, a comprehensive overview of 3D GIS was published (Dell'Unto and Landeschi 2022). Dell'Unto and Landeschi bring together several concise chapters covering the application of GIS and 3D technologies in archaeology, both on their own and in combination. They provide a basic overview of the methods and a comprehensive history of development, enriched with case studies and detailed descriptions of the respective methodologies. In their view, the main applications of 3D GIS include documentation and excavation evaluations, surface and subsurface analysis, visibility analysis (on both small and large scales) and volumetric analyses. Future developments are seen, for instance, in sensory analyses, such as movement or perception analysis. The latter uses the 3D GIS environment of a reconstructed house for VR applications and viewpoint analysis, which might advance our understanding of architectural perception using modern audiences. This example shows the enormous possibilities that 3D GIS can open up in the future.

Another emerging subfield, which was not covered by the survey, is the application of HBIM (Heritage Building Information Modelling) on the basis of 3D modelling (cf. Bagnolo et al. 2019; Banfi 2020). None of the answers in the survey hinted at the use of such approaches, although, as with GIS, the focus of the survey did not lie on the further use and evaluation of the 3D objects acquired.

11.3.4 Archiving

The survey revealed a potential lack of institutional guidelines in relation to archiving. Data management plans (DMP) appear to be rarely elaborated or adopted, at least from the perspective of the respondents. This contrasts with the fact that most scientific funding institutions explicitly require DMPs, for instance the Swiss National Science Foundation (SNSF, http://www.snf.ch/de/derSnf/forschungspolitische_positionen/open_research_data/Seiten/data-management-plan-dmp-leitlinien-fuer-forschende.aspx, accessed 17 Jan 2021), the Deutsche Forschungsgemeinschaft in Germany (DFG, https://www.dfg.de/foerderung/antrag_gutachter_gremien/antragstellende/nachnutzung_forschungsdaten/, accessed 17 Jan 2021) and the European Research Council (ERC, https://erc.europa.eu/sites/default/files/document/file/ERC_info_document-Open_Research_Data_and_Data_Management_Plans.pdf, accessed 17 Jan 2021).

We assume that orally transmitted and only lightly formalised 'best practice' guidelines play an important role in archaeology. These are likely to exist and be implemented in the majority of institutions and working environments. If such 'best practices' are in place, there is usually no need for formalised DMPs, unless a specific funding scheme requires one. This entails a large variety of different solutions for archiving and data management that take into account local specificities. A set of overarching guidelines seems to be a widespread desideratum among the respondents. Should such guidelines be developed in the future, they must take this diversity into account. One of the major challenges in elaborating such guidelines is likely to be the need to offer sufficient flexibility, whilst covering diverse application scenarios.

A second challenge revealed by the survey concerns the different needs of the specialists working in different fields. One important issue is that project duration can differ significantly depending on the working environment. Freelancers, research institutions and heritage-protection authorities deal with different project durations in their routines. Heritage-protection authorities, for instance, have much longer timeframes in which to plan and operate, as opposed to freelancers who mostly work on short-term projects. Short-term projects place other demands on data management systems than long-term projects do. The exact differences between the needs of different kinds of institutions and professional contexts in archaeology must be examined more closely and better understood if future guidelines are to be adequate and effective. Most respondents were aware of this difficulty, as it was often cited in the survey as a probable reason for potential non-compliance with guidelines.

Furthermore, the interoperability of the data and outputs that are compiled, produced and processed must be seen as a third challenge. The high level of trust in the existing archiving solutions that was recorded probably ought to be critically interrogated. As the survey shows, in addition to JPEG and TIFF formats, RAW formats are also often archived. Due to their manufacturer-specific peculiarity and diversity, however, long-term interoperability is doubtful. It is striking that sustainable long-term solutions are only seldom put in place in data management. Here, it will be of the utmost importance to find simple solutions that can be implemented in 'daily' working conditions and workflows. In our opinion, the long-term archiving of 3D data (including derivatives) is one of the most important challenges raised by the digitalisation of the archaeological professions.

Topics that have, until recently, only seldom gained attention when discussing 3D data in archaeology are data security and protection, the resilience of the digital infrastructure and its environmental footprint (for a broader discussion, see, e.g., Bridle 2018; for a focus on archaeological data, see, e.g., Huggett et al. 2018). Awareness about these topics is reflected in the oft-stated requirements for the archiving of 3D data. In addition to data security, easy access and handling of the data is also perceived as a requirement, as is the server infrastructure being located in one's own country, which is once again connected to data security and legal issues.

Not considered a requirement by the respondents, the public accessibility of data seems to be significantly less important than data security. This circumspection towards publicly accessible data can mainly be seen in the questions concerning the accessibility of the database and archive. Most participants stated that access is restricted to the institution or even to smaller circles of people. Public access is mainly provided by research institutions, but even there, it is rather unusual, a situation that is at odds with various initiatives that have been working intensively to promote the more open handling of research data for several years, such as the FAIR principles (Wilkinson et al. 2016).

At present, increased efforts are being made at various political levels to tackle the challenge of long-term archiving. This is accompanied by efforts to develop a common baseline upon which guidelines could be developed. As such, the European Union recently implemented a new, comprehensive approach to digitalisation. Within this framework, several projects have been launched in the last two years that explicitly deal with 3D data and cultural heritage (EU ERA Chair in Digital Cultural Heritage: Mnemosyne: DOI: 10.3030/810857, accessed 17 Jan 2021; study on quality in 3D digitisation of tangible cultural heritage: https://ec.europa.eu/digital-single-market/en/news/study-quality-3d-digitisation-tangible-cultural-heritage, accessed 17 Jan 2021). Furthermore, since 2019 there has been a declaration of intent from 27 European states to cooperate more closely in the digitisation of cultural heritage (https://ec.europa.eu/digital-single-market/en/news/eu-member-states-sign-cooperate-digitising-cultural-heritage, accessed 17 Jan 2021). In August 2020, 10 basic principles and tips concerning digitisation and cultural heritage were published by a task force (https://digital-strategy.ec.europa.eu/en/library/basic-principles-and-tips-3d-digitisation-cultural-heritage, accessed 16 Aug 2022):

The principles and tips cover the decision-making process, from whether or not to digitise an object to the definition of the audience and whether or not the digitisation process should take place in-house (principles 1–3). The user is encouraged to critically rethink whether digitisation is needed and for what purpose. However, the principles fail to consider data-security issues or the environmental impact of an ever-expanding digital archive. Here, a broader discussion on digitisation and its societal and environmental impacts is needed.

Among other things, the principles also explicitly identify the need to clarify the licencing beforehand and to ensure the use of open data formats and the inclusion of machine-readable metadata, thereby encouraging broad and open access (principle 4).

Data formats and archiving data are tightly connected to the quality and resolution of the models that are targeted by the project. Moreover, the required data formats may differ according to the use case. Principles 5 and 6 recommend defining the minimum quality needed, but aiming for the highest affordable quality and offering access with at least one open data format. As the survey showed, it is important to deal with these issues, as the open-access policy does not seem to be widely applied in relation to 3D outputs in archaeology and cultural heritage. At the same time, the evaluation of our survey showed that, of the recommended open data formats, such as glTF, X3D, STL, OBJ, DAE, PLY, WRL, DICOM or IFC, at least two are widely used (i.e. OBJ and PLY).

Principles 7, 8 and 9 focus on the long-term preservation of the outputs, the adequacy of techniques and workflows, as well as the protection of the originals during the process. While principles 8 and 9 align with what should be expected by experts from the field of archaeology/cultural heritage, principle 7 refers to a much less clear issue. The document states that researchers should be encouraged to store everything, even the software used to open the stored files. As the survey showed, this is still where most challenges connected to the 3D digitisation of cultural heritage lie. Among other issues, such as the question of the durability of software and hardware, the apparent lack of use of open software applications seems striking. The principles, at least, explicitly call for as much use of open solutions as possible.

Finally, principle 10 encourages the reader to invest in acquiring knowledge about and conducting further research into 3D technologies. The importance of this point cannot be overstated.

The Cyprus University of Technology started coordinating a consortium to study the relevant elements of the 3D digitisation of cultural heritage. In order to do so, an online survey to determine the relevant parameters for quality within the complex digitisation process was conducted between the summer and winter of 2020. The entire study included the definition of different degrees of complexity concerning the digitisation of Cultural Heritage, the identification of the technical and non-technical parameters defining the quality of 3D objects, the identification and analysis of existing formats, standards, methodologies and guidelines, the analysis of past or ongoing 3D digitisation projects with a benchmark character and, finally, linking the results of these sub-studies. The aim in the long run seems to be the establishment of applicable guidelines serving the standardisation of the digitisation of tangible cultural heritage (http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=69940, accessed 17 Jan 2021).

Europeana, a Europe-wide museum platform, provides access to millions of digital assets from European museums, galleries, libraries, archives and research institutions. For several years, Europeana has been stepping up its efforts to achieve interoperability and find ways of making 3D data available (Fernie et al. 2019). In this context, they have been able to acquire extensive experience in the merging of heterogeneous 3D data. Problems such as low standardisation, high complexity, large amounts of data, low interoperability and a lack of metadata became apparent, and finding a solution for these problems was identified as an objective. The current work of the IIIF 3D Group, which cooperates with Europeana, seems promising in this matter. The International Image Interoperability Framework IIIF was developed in 2011 and proved to be a highly successful interoperability environment for digital two-dimensional images. The aim is now to develop similar solutions for 3D data (Haynes 2020). Other technological developments are also currently underway, which could enable not only better interoperability and archiving, but also the easier handling of 3D assets in the future. A team led by Touradj Ebrahimi from the EPFL in Switzerland is working on machine-learning-based algorithms to compress 3D data. The neuronal networks are trained both in the compression of joint and separate geometric and textural information from point cloud contents. The approach is promising, demonstrating better performance in certain aspects than the MPEG anchor used as a comparison. The novelty of the approach lies above all in the combined compression of geometry and texture (Alexiou et al. 2020). New impulses and solutions for archiving, exchanging and operability may also be expected to emerge from this research.

In addition to the European effort to formulate guidelines and tackling the challenges of digital long-term storage, other political bodies have also recognised the need to improve infrastructure and software. On the national level, for instance, the Deutsche Forschungsgemeinschaft (DFG) in Germany is working on developing national research-data infrastructure (Nationale Forschungsdateninfrastruktur, NFD), while the Consortium NFDI4Objects is attempting to add a section in NFD which explicitly tackles the needs of object-based research (https://www.nfdi4objects.net/, accessed 17 Jan 2021) Meanwhile, in Switzerland, efforts are being made to build a digital archive of cultural assets, which explicitly includes 3D models and other digitised data. A first study evaluated possible risks of digital cultural assets that need to be dealt with, including the resilience of existing electronic infrastructure. In the future course of this project, valuable experience and knowledge should be gained that is relevant to a wider range of applications (Albisettli 2020).

In addition, the association of the archaeological-technical excavation staff of Switzerland (VATG) with a working group (D!G) is working on an intensified exchange to bundle together know-how and experience. They are also attempting to impose a certain standardisation of methods (http://vatg.ch/wp-content/uploads/dig-grobkonzept-1.pdf, accessed 17 Jan 2021). This can be seen as a bottom-up movement, which is trying to self-organise in terms of its resources and possibilities.

11.4 Conclusion

The survey presented here gives an overview of the current significance of image-based 3D technology in archaeology. The most important goals, which are the documentation of excavations and research through 3D data, could be attained by employing the most frequently used software application (Metashape from Agisoft LLC) and data formats for input (JPEG, TIFF and RAW formats) and output (OBJ, PLY and GeoTIFF). The image-based technologies discussed, together with other methods like laser and structured light scanning, already have a place among the many tools used in archaeology. Since the application of these technologies was mostly said to be still at the testing phase, we can expect a continuous increase in their use and integration in the future. Archiving data is one of the major challenges that arises in all the working fields of archaeology. There are no well-established institutional guidelines, and formalised data management plans are also rarely available. In addition, the survey results indicate that the different fields of archaeological work (i.e. freelancers, research institutions and heritage-protection authorities) have different needs. Potential future guidelines must be acceptable to all the different stakeholders. Another unsolved problem concerns the interoperability and long-term storage of the data.

On the international and national levels, efforts are underway to tackle most of the apparent challenges, such as storage infrastructure and long-term archiving. Nevertheless, difficulties remain, such as the still-missing open-source solutions for image-based 3D reconstructions (including georeferencing). At the same time, the impact of already-published tips and principles or other best practices remains unclear. It is often the case that the best-possible solutions cannot be implemented, due to restrictions from funding schemes and the need to work within the (often limited) budgets of the institutions in question. In an utopian view recently taken by Hodel (2020), the entire data acquisition process would be undertaken with high-resolution sensors (image-based 3D modelling could be an example of this) and archaeology could be reinvented without material boundaries by a digital humanist. The additional processed data would then be included in linked-open-data triple stores and be organised using elaborate ontologies. The whole would then be published in open repositories and further enhanced with metadata, which could be blockchain-like, being linked and enriched even further with results, interpretations and critiques. This could, in turn, provide the basis for research projects and/or digital exhibitions.

This survey has shown that archaeology is currently undergoing a process of reinvention with reference to the aspects outlined above. But rather than being reinvented by a digital humanist, this process is taking place bottom-up and on the job – or to put it in the words of Costopoulos (2016): 'We are building a digital archeology by doing archeology digitally [sic]." While this may add to the difficulties in establishing overall standards, it also ensures the application of a diverse range of models and tools. That said, an inherent part of the digitalisation process is the negotiation of standards concerning the classifications and the ontologies behind them. Of importance in this context for the 3D documentation is the epistemological grounding of the capture of documented data (How is it captured? How does the method distort the evidence? Etc.). Its enrichment, analysis, dissemination and storage are further domains in which classifications and standards are applied. This application is mainly shaped by research projects, which produce data, but all the later stages also come into play, leading to the fragmentation and diversity which has been observed. As Hodel (2020) puts it in his conclusion, the digital turn will be less a top-down revolution than an evolution that requires an active contribution from all practitioners. While this latter call can and must be agreed upon, increasing efforts by supranational organisations to increase standardisation must be watched more closely, while archaeologists and other practitioners in cultural heritage and related fields must become more involved. The issues at stake are central for the field as a whole and should not be left to digital specialists or funding bodies alone.

References

Albisettli L (2020) Ein Bergungsort für digitale Kulturgüter. NIKE Bull 2020:18–21

Alexiou E, Tung K, Ebrahimi T (2020) Towards neural network approaches for point cloud compression. In: Tescher AG, Ebrahimi T (eds) Applications of digital image processing XLIII. SPIE, Washington, DC, 11510 08

Bagnolo V, Argiolas R, Cuccu A (2019) HBIM for archaeological sites: From SFM based survey to algorithmic modeling. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-2/W9 57–63. https://doi.org/10.5194/isprs-archives-XLII-2-W9-57-2019

Banfi F (2020) HBIM, 3D drawing and virtual reality for archaeological sites and ancient ruins. Virtual Archaeology Review 11(23):16. https://doi.org/10.4995/var.2020.12416

Blaich MC, Ludwig C, Salzmann C (2019) Monitoring von Geländedenkmälern mittels Unmanned Aerial Vehicels (UAVs) und Structure from Motion (SfM): Erste Erfahrungen auf den Pfalzen Werla und Königsdahlum. Nachrichten aus Niedersachsens Urgeschichte 88:271–293

Bridle J (2018) New dark age. Technology and the end of the future. Verso, London/Brooklyn

Cignoni P, Callieri M, Corsini M, et al (2008) MeshLab: an open-source mesh processing tool. In: Sixth Eurographics Italian chapter conference. pp 129–136

Costopoulos A (2016) Digital archeology is here (and has been for a while). Front Digit Humanit 3. https://doi.org/10.3389/fdigh.2016.00004

Dell'Unto N, Landeschi G (2022) Archaeological 3D GIS. Routledge, London

Fernie K, Blümel I, Corns A, et al (2019) 3D content in Europeana task force. Europeana Network Association Members Council Task force report https://pro.europeana.eu/files/Europeana_Professional/Europeana_Network/Europeana_Network_Task_Forces/Final_reports/3D-TF-final%20report.pdf. Accessed 16 Jan 2021

Hagenauer S (ed) (2020) Communicating the past in the digital age. Proceedings of the international conference on digital methods in teaching and learning in archaeology (12–13 October 2018). Ubiquity Press, London

Haynes R (2020) Europeana & IIIF 3D: Next steps & added dimensions? In: EuropeanaTech Issue 14: 3D. https://pro.europeana.eu/page/issue-14-3d#europeana-iiif-3d-next-steps-added-dimensions. Accessed 16 Jan 2020

Herzog I, Lieberwirth U (eds) (2016) 3D-Anwendungen in der Archäologie. Computeranwendungen und Quantitative Methoden in der Archäologie, Workshop der AG CAA und des Exzellenzclusters TOPOI 2013. Berlin

Hodel T (2020) Perspektivenwechsel: Zwei Disziplinen aus Sicht der Digital Humanities – oder wie sich die Geisteswissenschaften im Digitalen (selbst) finden. Zeitschrift für Schweizerische Archaeologie und Kunstgeschichte ZAK 77:101–110. https://doi.org/10.7892/BORIS.147227

Howland MD (2018) 3D recording in the field. Style without substance? In: Levy TE, Jones IWN (eds) Cyber-archaeology and grand narratives. Digital technology and deep-time perspectives on culture change in the Middle East. Springer, Berlin/Heidelberg/New York, pp 19–33

Huggett J, Reilly P, Lock G (2018) Whither digital archaeological knowledge? The challenge of unstable futures. J Comp Appl Archaeol 1:42–54. https://doi.org/10.5334/jcaa.7

Jones CA, Church E (2020) Photogrammetry is for everyone: structure-from-motion software user experiences in archaeology. J Archaeol Sci Rep 30:102261. https://doi.org/10.1016/j.jasrep.2020.102261

Katsianis M, Tsipidis S, Kotsakis K, Kousoulakou A (2008) A 3D digital workflow for archaeological intra-site research using GIS. J Archaeol Sci 35:655–667. https://doi.org/10.1016/j.jas.2007.06.002

McCarthy JK, Benjamin J, Winton T, Duivenvoorde W (2019) 3D recording and interpretation for maritime archaeology. Springer, Berlin/Heidelberg/New York

Pakkanen J, Brysbaert A, Turner D, Boswinkel Y (2020) Efficient three-dimensional field documentation methods for labour cost studies: case studies from archaeological and heritage contexts. Digit Appl Archaeol Cultural Herit 17:e00141. https://doi.org/10.1016/j.daach.2020.e00141

Unger J, Hemker C, Lobinger C, Jan M (2020) VirtualArch: making archaeological heritage visible. Internet Archaeol 54. https://doi.org/10.11141/ia.54.2

Vollmer-König M (2017) Digitale Verfahren in der Bodendenkmalpflege. In: Franz B, Vinken G (eds) Das Digitale und die Denkmalpflege. Bestandserfassung, Denkmalvermittlung, Datenarchivierung, Rekonstruktion verlorener Objekte. Chancen und Grenzen im Einsatz digitaler Technologien. Veränderungen in der Praxis von Denkmalpflege und Kultursicherung. Holzminden, pp 56–59

Wilkinson MD, Dumontier M, Aalbersberg IJJ et al (2016) The FAIR guiding principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18

Winkler A (2020) Kallnach, Challnechwald. Eine Grabhügelnekropole aus der älteren Eisenzeit. Erkenntnisse aus dem ersten Grabungsjahr. In: Bildungs- und Kulturdirektion des Kantons Bern Archäologischer Dienst des Kantons Bern P (ed) Archäologie Bern/ Archéologie bernoise 2020 Jahrbuch des Archäologischen Dienstes des Kantons Bern 2020. Annuaire du Service archéologique du canton de Berne 2020:49–51

Chapter 12
Archiving the Third Dimension: Production, Maintenance and Use of 3D Models in Cultural Heritage Management

Kristin Kruse and Esther Schönenberger

Abstract In 2017, the Archaeology Department of the Canton Zurich defined photogrammetry in Agisoft Metashape as a new standard. The years have shown the advantages of the method, especially when documenting complex 3D structures, like skeletons or ruins, on site. While generating 3D models was a well-trodden path, the storage of 3D models needed some exploration. The first challenge was to incorporate 3D data into a pre-existing archive system. The second challenge was to secure both easy access for everyone and long-term storage at the same time. We propose a solution where access and storage are treated as two separate issues. This allows the content to be viewed without technological restrictions (e.g. as 3D PDF or VR application). While independently the same models are stored in a normalised geometry file (e.g. OBJ file) for long term use. Since long-term standards for 3D data have yet to be established, we have decided to provide a temporary backup system by keeping the raw data (photos) together with the processing report for replication purposes. Our solution comes with a lot of redundancy. However, this is still a trial and error approach, one that we would like to work on with fellow 3D enthusiasts.

Keywords Archive · 3-dimensional · Photogrammetry · Open archival information system (OAIS)

12.1 Introduction

The value of photogrammetry for documenting archaeological features is well proven (cf. De Reu et al. 2014). But has the technology been fully established within archaeological procedures regarding rescue excvations? What criteria must a technology meet in order to be described as established? Since archaeology is a science in which research is seldom based on the object itself but almost always on the

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primary documentation, ensuring the preservation of that primary documentation is intrinsically crucial. So long as this cannot be guaranteed in the case of image-based modelling, the technology, strictly speaking, should only be used, at most, as a supplementary method of documentation.

As a state enterprise, the Archaeology Department of the Canton Zurich is tasked with locating areas of potential archaeological importance and, if necessary, carrying out rescue excavations. The documentation is kept and made available for future research. The results of excavations are also made accessible to the public.

Since 2017, the Department has been using photogrammetry as a standard method of documentation. The advantages of this method were apparent right from the start. However, staff were not properly trained yet, there were no standards on which to base procedures, and, above all, an inadequate archival infrastructure meant that results could not be properly archived. These problems prevented the technology from becoming fully established, and so a project was initiated, tasked with finding solutions. The resulting concept envisages being able to archive data from 2021 onwards. The archive will then be kept under regular review until 2027, in the hope that by the end of the project, we will be in a position to propose a long-term archiving solution. Section 12.2 of this article examines the areas of application of image-based modelling and attempts to infer from these the future requirements of archive users. In Section 12.3 these requirements are integrated into an archive system.

Note: Currently, the project—like this paper—is addressing only data relating to excavation documentation, not to documentation of findings. The project will also address the archiving of laser-scan data, but that is beyond the remit of this paper.

12.2 Areas of Application of Photogrammetry

Traditionally, the documentation of archaeological excavations by our Department rests on three pillars:

1. Photographs, which give an objective impression of the situation being documented.
2. Drawings, which precisely localise and interpret the features (cf. Morgan and Wright 2018).
3. Journals, which describe the features in words.

The documentation is used in archaeological research and made available to the public in an appropriate form.

3D recording plays a role in almost all areas of our work and brings with it archiving requirements, as described below.

12.2.1 Objective Primary Documentation

Basically, 3D recording gives an almost objective spatial impression, which reflects, without commentary, the situation on site. In this way, it is similar to traditional photography (cf. Fouriaux, Introduction of Chap. 5 in this book). Photogrammetry really comes into its own where photography comes up against its limitations: when features present strongly three-dimensional characteristics and therefore cannot be recorded in a single photograph. In the case of walls, kilns, wells, baths—in short, any structures with strongly three-dimensional characteristics, photogrammetry brings added value. Because of the additional information it includes, its use should be imperative in the documentation of such features, in so far as the necessary resources are available. On the other hand, an simple, flat archaeological layer can be recorded without difficulty by a photograph. When the image has been rectified, it affords almost exactly as much information as photogrammetry. In this case, 3D recording does not need to be used.

3D models make it possible to examine features from a single image and gain an impression of their totality, instead of having to mentally piece together separate images to make up the whole (Fig. 12.1). As well as strongly three-dimensional features, 3D images can thus also be used to capture complex, cross-trench stratigraphic sequences.

Burials are a particular case in point. Skeletons themselves present a high degree of three-dimensionality and are hard to record satisfactorily with photographs. If there are grave goods as well, the situation becomes even more complex. Burials rich in grave goods are routinely recorded three-dimensionally; those without grave

Fig. 12.1 Example of a complex structure, a 3D model of an oven. Excavation of a medieval monastery in Winterthur, Switzerland. (Image: Kantonsarchäologie Zürich)

goods may be too, depending on whether anthropological questions require a more detailed view of the skeleton.

The need for an archive to offer objective documentation is self-evident. Future researchers must be able to extract new knowledge from archived material. In the case of photographs, archive users should be able to call up and examine very high-resolution images via a database. Similar requirements exist in the case of photogrammetry. Users want to be able to make full use of the images, in other words, to examine them in three-dimensional space and in sufficiently high resolution, without the need for pre-existing technical expertise in working with 3D models. Since the 3D model contains geographical information, they also need to be able to take measurements or retrieve coordinates.

This calls for a viewer with an easy-to-use, device-independent navigation and orientation function.

12.2.2 Localisation and Interpretation

The products of 3D recording are also used as the basis for the second pillar of excavation documentation mentioned above: site drawings. These traditionally have two purposes:

1. Localising the feature in its surroundings
2. Interpreting the feature

Traditionally, drawings are made in the field on the basis of a simple survey grid. Measuring every stone by hand is very laborious. In the case of complex objects, such as courses of brick or masonry, drawings are increasingly being made from orthophotos, which, in turn, are computed from photogrammetric images (cf. Brünenberg et al., Chap. 4 in this book). There may be other reasons, apart from time pressure, for employing this procedure; for instance, if the feature concerned is located at a great height or at the bottom of an inaccessible trench and therefore poses safety concerns (Fig. 12.2). Here, too, an orthophoto can provide the basis for the excavation drawing. The orthophoto itself is part of the archaeological documentation and must therefore be preserved in the interests of providing a complete trail of scientific evidence. The most important aspect of the orthophoto, apart from the actual image data, is the associated geoinformation, and this, too, must be available in the archive.

12.2.3 Archaeological Research

Our Department still has relatively little experience of using 3D models in scientific research. Up until now, the visual aspect of image-based modelling was the main contribution to understanding certain findings. For this usage, the archival

Fig. 12.2 Example for a structure with physically inaccessible features. 3D-model of the medieval fortification 'Erdmannliloch' in the Canton of Zurich, Switzerland. The documentation was made due to slow destruction of the findings by use of hikers. (Image: Kantonsarchäologie Zürich)

Table 12.1 Exemplary compilation of analysis methods based on 3D recording

Method	Examples	Data used	Programmes used
Analyses of illumination in interior spaces	Santagati et al. (2019)	Textured mesh	BIM-Software (Revit Autodesk)
Examination of surfaces invisible or poorly visible to the naked eye	Analysis of petroglyphs:	Untextured mesh	
	Horn et al., Chap. 6 in this book, Reinhard (2019) and Zotkina and Kovalev (2019)		QGIS
	Evidence of use:		
	Zupancich (2019)		ArcGIS?
Comparison of shapes of geographically separated objects, including automated comparison using generative modelling	Schinko et al. (2019)	Untextured mesh	–
	Trinkl et al., Chap. 7 in this book	Textured mesh	
Reconstruction for the purpose of forming hypotheses	Yamafune (2016)	Untextured mesh	Maya
	Bruderer (2020)	Textured mesh	Cinema 4D
Movement in 3D-environment	Fouriaux, Chap. 5 in this book	Textured mesh	Blender, QGIS, Gephy

requirements have already been discussed in Sect. 12.2.1. 3D models can also, however, assume an active role in archaeological research.

Unfortunately, there has not yet been any comprehensive compilation of analytical methods which rely on 3D recording. Our attempt, shown in Table 12.1, therefore makes no claim to be complete.

Since the applications are extremely varied, it is difficult to tell, when archiving data for future use, in what format or resolution they may be needed. Moreover, new research methods will probably be developed in the future. Ours is therefore merely an initial, tentative approach to the problem:

The types of analysis listed, all use the generated mesh. On the other hand, texture is not relevant for some of the applications; it is much more important that the mesh offers high resolution and high edge definition in the area of the relevant features. If the 3D model is to be used as the basis for a reconstruction, however, texture is often needed, while high resolution is somewhat less important.

When creating and archiving 3D images, therefore, it makes sense to try and think of every probable future research question at the outset. However, since it is seldom possible to anticipate every future area of enquiry at the moment when the photograph is taken, care should be taken to ensure that a high-resolution mesh can be exported from the archive. At the same time, texture should not be neglected, since it may be needed in the case of a reconstruction. Moreover, it should be possible to open the data in widely used modelling programs ranging from ArcGIS Pro to Cinema 4D; in other words, data should be stored in as widely-used a format as possible.

12.2.4 Conveying Information to Specialists and the General Public

Just as difficult to envisage as the future needs of scientific research are the future methods by which information will be conveyed to both specialists and the general public. There are many different ways in which 3D recording can be used to present archaeological features and these are constantly changing.

Currently, our Department makes 3D images available to the public in two ways.

- Via platforms like Sketchfab, 3D models can be embedded into blog posts or linked to scientific publications. Blog posts are a way for our department to bring our daily work to a broader public. We did not yet use links to sketchfab in publications for scientific audience yet, but are working on the framework now.
- In the context of public outreach work or scientific conferences, we use virtual- or augmented-reality applications to display 3D recordings via smart devices or 3D glasses. We have implemented those applications in specific, temporary live events. There was only limited interaction with the 3D-models and narrative was given by live persons.

We have had an overwhelming response, particularly from the general public, to augmented-reality applications. Even people who are not tech-savvy find them easy to access and experience the vanished features almost as if they were real.

The ability to bring physically lost features back to life in this way has been clearly specified as an important requirement by the Department. For this reason, it must also be possible for archived data to be retrieved and processed for visualisation. Visualisation relies on a mesh. Texture is essential, however, since here, unlike in spatial analysis, the visual impression is what counts. In many applications, the resolution and texture of the model currently have to be greatly reduced. Since the requirements of the transporting media are constantly changing, it must be possible to export a product from the archive that is suited to the medium concerned. The archived image must therefore be available in a format whose resolution is easily scalable.

12.2.5 Summary of User Requirements for a 3D Data Archive

We have now described the various areas in which 3D models play a role in the documentation of archaeological excavations. For every area, we have worked out what demands would be made of the archive. To summarise (Fig. 12.3) supported by the results of our study:

- **Everyday users need simple access:** As objective primary documentation, 3D models must be able to be examined and measured in three dimensions by every archive user without needing to use a complex 3D software.
- **Specialists need high-resolution data:** for archaeological research, it must be possible to export a high-resolution mesh with texture.
- **Mediation requires situation-specific data:** for visualisation for educational purposes, it must be possible to export a mesh with texture in a resolution suitable for the medium being used.
- **The work of the Department requires georeferencing:** If orthophotos are created, these should be retrievable along with their geoinformation.

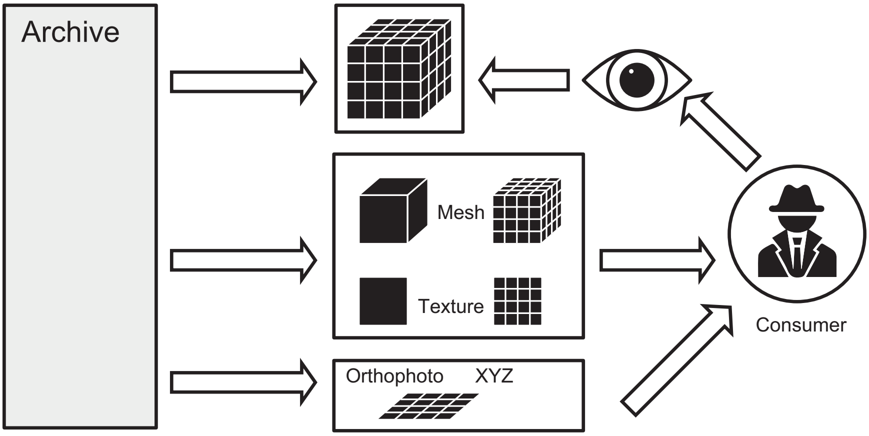

Fig. 12.3 Simplified user requirements for a 3D data archive

In terms of user analysis, it can be established that where the use of 3D models is concerned, there are different user groups (ordinary users vs. specialists) with different requirements for data quality and data representation. It is now a question of incorporating these different needs into the archive design.

12.3 Archiving Photogrammetry

12.3.1 New Challenges

The requirements summarised in Sect. 12.2.5 for the long-term archiving of 3D data demonstrate a multiplicity of sometimes conflicting demands. It is therefore clear that, unlike in the case of traditional text and image data, there is no one data format for 3D data that can cater for all requirements at once (e.g. PDF/A for texts or TIFF for images). There is therefore a need for a radical rethinking of old archive repositories—which have usually evolved from analogue structures. Instead of trying to find a tailored solution for each new problem, it would be much more sustainable to integrate scope for technological development as part of the archiving process. Thought therefore needs to be given to:

- **Separating access from archiving:** in order to give user requirements more space and the opportunity for development, the way data are used must be considered separately from the way they are archived.
- **Archiving of datasets:** pragmatic solutions are needed for storing data objects which consist of several individual files (e.g. ZIP-File, Georeferenced Images)—something which is becoming increasingly common, particularly with interactive formats.
- **Future-oriented archive systems:** there is a need for fundamentally simpler and at the same time more flexible archive systems, into which future data formats can easily be incorporated.

This required approach is supported by the 'Open Archival Information System', which we consider to be the optimal basis for archiving 3D data, as well as for other future formats.

12.3.2 The Open Archival Information System (OAIS)

OAIS is a reference model for long-term digital archiving. It has its origins in international space travel and was first presented by the Consultative Committee for Space Data Systems (CCSDS 2012). Since 2003, it has been listed as an international standard, ISO 14721, and has been constantly expanded (ISO 2020). As a reference model, OAIS is simply a concept for digital long-term archiving which provides for a clear division of roles, defined task areas and a shared terminology. It does not, however, specify the technical means, detailed procedures, and agents by which the concept should be implemented. It therefore offers a shared basis for digital long-term archiving which can be adopted by any archive and implemented in a way that meets everyone's own requirements (CCSDS 2012, Chap. 1.2; applied in KOST 2020).

In our current project, the emphasis lies on the storage of the same information in multiple form, according to different application purposes. This type of procedure can be operationalised in OAIS using so-called 'information packages'

OAIS information packages are containers for data, created for specific areas of application, for which the same sets of archiving rules apply. OAIS defines three areas of application: data ingestion, data archiving, and data access. This makes it possible to deposit the same information in three different information packages, with different data formats and different rules. The definition of these formats and rules must be established by all the participants in advance. OAIS defines three roles of participants which should be taken into account when making this decision: Producer, Management and User. With their complementary points of view, the occupants of these roles have a shared responsibility for developing a suitable infrastructure, efficient workflows, and a sound archiving strategy.

12.3.3 The OAIS Archiving Strategy

Based on the OAIS reference model, we are now able to present a first archiving strategy for photogrammetry in the Archaeology Department of the Canton Zurich (Fig. 12.4). It was developed through wide-ranging discussions within the

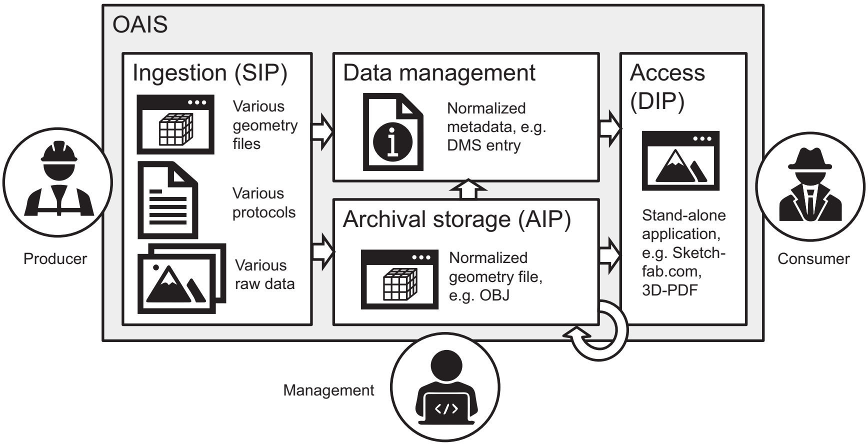

Fig. 12.4 Archival strategy for the storage of 3D data in the Archaeology Department of Canton Zurich based on the OAIS reference model

Department, supplemented by specialist input from research groups (DIG 2020; Hostettler et al. 2019), specialist units (e.g. KOST 2020; Library of Congress 2019) and some feedback from universities. This broad-based exchange ensures the equal involvement of producers, managers and users right from the start.

In everyday use, the three roles are performed by mainly internal personal with the following definitions, tasks and responsibilities:

- **Producers:** members of the internal technical staff with specialist knowledge of 3D recording. Since image-based modelling requires specialist expertise, the producer's role is clearly important. They are not only responsible for the correct production of data but will need to be consulted by management for years to come about such things as data output to third parties and data conversion.
- **Management:** internal, professionally trained archive staff tasked with long-term archiving. This includes regular checking and, if necessary, reconfiguration of data in the long-term archive to ensure that data formats remain readable and up-to-date (Life Cycle Monitoring).
- **Users:** internal staff members and external archive users with different professional, qualitative and technical expectations of 3D models (see Sect. 12.2). It is their responsibility to present their requirements or new needs to the management in a timely and precise manner.

When handling data, we strive for a clear separation between the areas of data ingestion, data archiving, data access and data management. Therefore, we work with a separate information package for each area. Furthermore, each area is defined with its own archiving rules and procedures:

- **Data ingestion of the 'Submission Information Package' (SIP):** in this initial area of application, all the information about the material for archiving created by a producer during a production process using their preferred software environment, is brought together. Particularly in the case of computer-supported applications, this usually involves proprietary project data in software-managed filing structures which are not generally suitable for archiving and need to be exported to more neutral data formats. In the case of 3D models, archive formats are usually agreed on in advance, allowing them to be created as end products by the producer and transferred directly into the AIP. If the SIP is from an external source, it is reviewed by producer and management and recommendations for export are made. Once the material has been successfully stored in the AIP, the SIP can be completely deleted.
- **Archival storage of the 'Archival Information Package' (AIP):**in this second area of application, electronic data are preserved for the future. These data are never deleted but are continually upgraded by management to meet current technological developments using Life Cycle Monitoring. In the case of 3D data, emphasis is placed on representing geometry and texture in the highest possible resolution, in the most software-neutral and standardised format, with the longest possible lifetime. This ensures that, once collected, data are available in their totality for derivatives and future applications (requirement of Sect. 12.2.3).

- **Data access of the 'Dissemination Information Package' (DIP)**:the third area of application involves collecting the data that were created along with the AIP, either in order to facilitate simpler day-to-day access (requirement of Sect. 12.2.1) or to allow it to be used with specialist applications (requirement of Sect. 12.2.4). Since the DIP is a derivative of the AIP, it is not archived long-term. This means that applications that are no longer readable or are technologically outdated can be completely deleted or replaced by newly created derivatives, allowing us to react flexibly to technological developments and to cater for fashionable, short-lived applications (requirement of Sect. 12.2.4).
- **Data management with a 'Document Management System' (DMS):** The fourth and last area of application does not have its own data package but manages the data units in the AIP and DIP. The DMS provides every item of data with descriptive additional details (metadata) about content, production, quality, archiving and much more. It also manages the allocation of data to particular information packages, which is vital for the correct implementation of the archiving strategy.

To summarise, the archiving strategy envisages the following data process: the producer generates the 3D model in the SIP and then exports it to the AIP, where it is permanently archived by management. At the same time, the producer always also creates a DIP for general access. If requested by a user, a special DIP can be created for data output from the AIP. If it is more convenient, specialists can also access the AIP directly.

12.3.4 Pilot Project 2021–2027

The strategy outlined in Sect. 12.3.3 will be adopted in the Archaeology Department of the Canton Zurich from 2021 onwards. There were several questions about the implementation and reliability that could not be satisfactorily answered in advance. For that reason, there will be an initial 5-year test phase, during which the strategy will be tried out and improved in the light of experience. The following questions will be crucial as we move forward:

- What data formats and data combinations will prove most successful as AIP?
- What data resolution will prove most practical for everyday use?
- What increase in storage capacity will be needed?
- How functional and amenable to further development is our chosen infrastructure?

In order to put the new system into operation, the workflow was operationalized using our Department software infrastructure (Fig. 12.5). We are currently using the software IMDAS Pro 6.0.18 by the Joanneum Research Institute with a standardised data model by the 'spatz/imdas' coordination group of the cantons of Grisons, Thurgau, Zurich and the principality of Liechtenstein. Therefore, IMDAS is serving

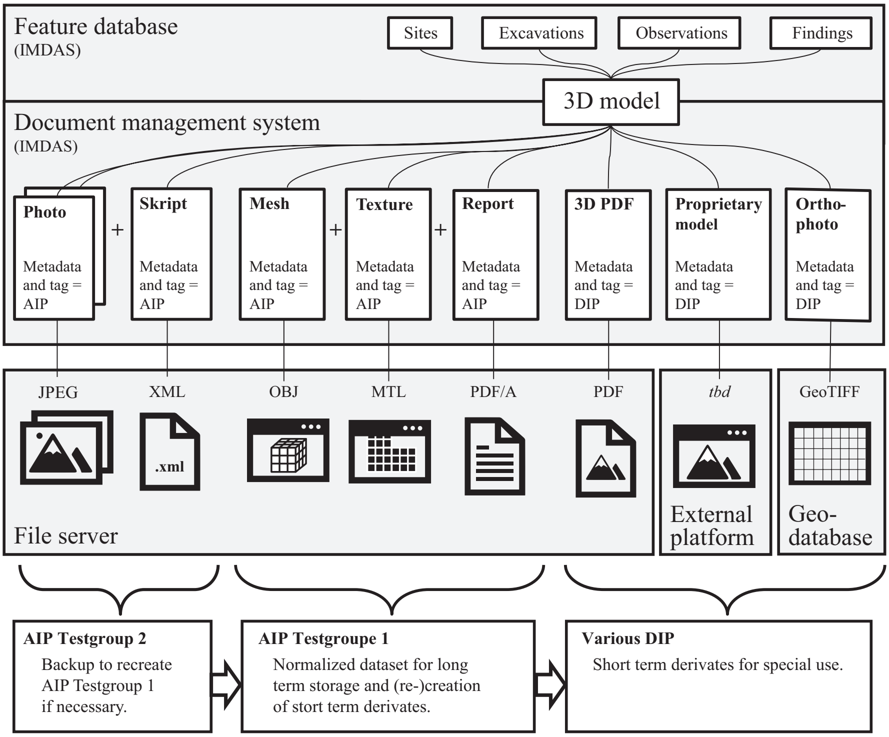

Fig. 12.5 Storage of 3D data in the current archive system of the Archaeology Department of Canton Zurich during the 5-year test phase

as our data management tool and our storage system. All the sites, excavations, observations and findings are recorded in this system. At the same time, IMDAS has an integrated DMS where all the media object that need to be archived can be registered, along with their metadata, and linked with the relevant features. In addition to the existing media categories—‘image’, ‘plan/drawing’ and ‘document’—a new category has been introduced for ‘3D model’. Every 3D model is input as a separate media object and given a unique identification number. This means, that it can be linked to its associated feature (e.g. excavation or observation), while also serving as a dossier for all the relevant individual data files associated with the model (requirement of Sect. 12.3.1, datasets). These individual files are recorded in the DMS as matching media objects on their own. Only their storage location can vary depending on their purpose.

To implement the new system, it was necessary to specify initial obligatory data formats. These had to be compatible with Agisoft Metashape, the software used by Canton Zurich for the production of photogrammetry (in the current software version 1.4.4). For the duration of the test phase, we will be working with two mutually independent Archival Information Packages (Fig. 12.5, AIP Test Group 1 and Test Group 2).

Test Group 1 aims at an end product which provides the highest possible resolution, is software-neutral, and can therefore go on to be used in the greatest possible number of different applications—the criteria specified for AIP in the internal archiving strategy. To meet these criteria, in our opinion, a high-resolution mesh or dense point cloud offers the best solution, since all other formats can be derived from it. The output is produced using two industry-standard files: Wavefront OBJ for geometry and a Wavefront MTL file for texture (Agisoft 2020, p. 161; Library of Congress 2019). The package is completed by an automatically generated Processing Report, which summarises the parameters and error deviations used in the modelling process and thus allows the model's sources to be critiqued (Agisoft 2020, p. 54).

In case the format chosen for Test Group 1 proves to be the wrong one, all the photos will also be temporarily archived. This will be done in a separate AIP, with the idea that the modelling can be repeated if necessary, supported by a computer-readable script that will allow the automated repetition of the most important modelling steps (Fig. 12.5, AIP Test Group 2). Agisoft Metashape offers a suitable, importable script in XML format (Agisoft 2020, p. 27), containing the final positions of the spatially oriented photos—or 'cameras', as they are called in Agisoft Metashape (Agisoft 2020, p. 19)—which are needed to compute the dense point cloud. Like most scripts, however, it is highly software dependent and time sensitive and will probably only be able to be opened directly in Agisoft Metashape for a limited time period. Test Group 2 is therefore not a real, long-term AIP solution. It is merely serving as a back-up system during the test phase and can hopefully be deleted in 2027.

All other files are optional derivatives, newly created, as described in Sect. 12.3.3, based on the AIP of Test Group 1, mainly using Agisoft Metashape. This leaves all doors open to provide users with an easily accessible and effective 3D experience. From 2021 onwards it will be possible, for example, to embed 3D models in blog posts using Sketchfab, or display virtual- or augmented-reality images via applications on smart devices in the context of public outreach work—just as requested in the first half of the paper.

12.4 Summary and Outlook

In this paper, the status of an on-going project at the Archaeology Department of the Canton Zurich is presented. This includes, for the first time, a concept for the archiving of 3D data. Photogrammetry is already an important component of excavation documentation and public outreach work in Canton Zurich, which will also become increasingly important in archaeological research in the medium term. However, the technology cannot yet be regarded as fully established, since data storage and archiving cannot be guaranteed. This should change by the time the project ends in 2027.

At the beginning of the project, a user-based analysis of requirements was carried out within the Department. This early canvassing of different points of view provided important insights for the subsequent formulation of a general archiving strategy. It turned out that when it came to using 3D models, a number of very different user groups presented different requirements with regard to data quality and data presentation (everyday users vs. specialists, public outreach staff vs. excavation staff). In response to this realisation, the possibility of multiple storage of information according to intended use was incorporated into the archiving strategy concept. This involved, in particular, separating archiving requirements from accessibility requirements. We adopted the Open Archival Information System (OAIS) as a suitable, up-to-date reference model, and this required us to define a clear distribution of roles within the Department, with relevant tasks and responsibilities. Preparations have also been made to put the strategy into operation. A five-year test phase for archiving 3D data will officially begin in 2021.

As this is one of the first ‘preservation plans’ for 3D data, we are about to submit our archiving strategy to the Swiss Centre for the Coordination of Long-Term Archiving of Electronic Documents (KOST 2020). So that others can benefit from our work. We will also report regularly on our experience in the recently created Swiss working group for digital excavation documentation (cf. DIG 2020). We hope that this article will lead to an international discourse to further facilitate the use, storage and re-use of photogrammetry.

References

1D model Agisoft (2020) Agisoft Metashape User Manual: Professional Edition, Version 1.6. Available electronically. https://www.agisoft.com/pdf/metashape-pro_1_6_en.pdf. Accessed 30 Sept 2020

Bruderer O (2020) Das virtuelle Modell in der Archäologie: Kontinuität des 3D-Mediums in Dokumentation, Analyse und Vermittlung. MA-Thesis, ZHdK Zurich University of the Arts

CCSDS Consultative Committee on Space Data Systems (2012) Reference model for an open archival information system (OAIS): Magenta book. Available electronically. https://public.ccsds.org/pubs/650x0m2.pdf. Accessed 30 Sept 2020

De Reu J et al (2014) On introducing an image-based 3D reconstruction method in archaeological excavation practice. J Archaeol Sci 41:251–262. https://doi.org/10.1016/j.jas.2013.08.020

DIG Arbeitsgruppe digitale Grabungsdokumentation (2020) DIG. http://vatg.ch/dig/. Accessed 30 Sept 2020

Hostettler M et al (2019) The 3 dimensions of digitalized archaeology: data management, scientific benefit and risks of data storage in archaeological image-based 3D-documentation. Session hosted at the 25th annual meeting of the European Association of Archaeologists (EAA), University of Bern, Switzerland, 5–7 September 2019

ISO International Organization for Standardization (2020) ISO 14721:2012, Space data and information transfer systems: Open archival information system (OAIS), Reference model. https://www.iso.org/standard/57284.html. Accessed 30 Sept 2020

KOST Koordinationsstelle für die dauerhafte Archivierung elektronischer Unterlagen (2020) Preservation Process der KOST. https://kost-ceco.ch/cms/preservation-process-der-kost-1.html. Accessed 30 Sept 2020

Library of Congress (2019) Sustainability of Digital Formats: Planning for Library of Congress Collections. https://www.loc.gov/preservation/digital/formats. Accessed 30 Sept 2020

Morgan C, Wright H (2018) Pencils and pixels: drawing and digital Media in Archaeological Field Recording. J Field Archaeol 43(2):136–151. https://doi.org/10.1080/00934690.2018.1428488

Reinhard J (2019) In rock we trust. In: Hostettler et al. 2019

Santagati C et al (2019) HBIM for the surveying, analysis and restoration of the Saint John the theologian Cathedral in Nicosia (Cyprus). International archives of the photogrammetry. Remote Sens Spatial Infor Sci XLII-2(W11):1039–1046. https://doi.org/10.5194/isprs-archives-XLII-2-W11-1039-2019

Schinko C et al (2019) Generative Modellierung: Verknüpfung von Wissen und Form. In: Kuroczyński P, Pfarr-Harfst M, Münster S (eds) Der Modelle Tugend 2.0: Digitale 3D-Rekonstruktion als virtueller Raum der architekturhistorischen Forschung. Computing in Art and Architecture, vol 2. arthistoricum.net, Heidelberg, pp 296–311. https://doi.org/10.11588/arthistoricum.515

Yamafune K (2016) Using computer vision photogrammetry (Agisoft PhotoScan) to record and analyze underwater shipwreck sites. Dissertation, Texas A & M University. Available electronically. http://hdl.handle.net/1969.1/156847. Accessed 30 Sept 2020

Zotkina L, Kovalev V (2019) Lithic or metal tools: techno-traceological and 3D analysis of rock art. Digit Appl Archaeol Cultural Herit 13:e00099. https://doi.org/10.1016/j.daach.2019.e00099

Zupancich A (2019) The application of 3D modelling and spatial analysis in the study of groundstones used in wild plants processing. Archaeol Anthropol Sci 11:4801–4827. https://doi.org/10.1007/s12520-019-00824-5

Chapter 13
Concluding Remarks – Coordinates for the Future of Digitalised Archaeology

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Abstract The diverse contributions in this book show that the main challenges for the field are a lack of standardisation, interoperability and open-source solutions, as well as of long-term archiving solutions. The contributions also show that efforts are being made to sustainably integrate 3D technologies into the field of archaeology. Within the broader context of digital archaeology, it is argued that, in addition to technical issues, attention must be paid to ethical considerations about the nature of technology, cultural heritage and accessibility. Finally, the entanglements of technology with violent contexts must also be critically assessed.

Keywords Digital humanities · Digital archaeology · 3D archaeology · Access · Interoperability · Long-term archiving · Ethics in archaeology

The aim of this book was to provide insight into current cutting-edge applications of 3D technology in archaeology, as well as to identify the most-pressing challenges

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that still need to be overcome. 3D archaeology is part of the vast subdiscipline of digital archaeology, whereby the focus lies on the digital capture, reconstruction and/or display of real-world objects in a 3D digital environment. The individual chapters that make up this book testify to the wide array of possible applications subsumed under the notion of ‘3D archaeology’, and even these do capture its full potential. Chapter 2 (Pendić and Molloy) gave a brief overview of the history of this method, emphasising the importance of FAIR data principles for future developments. Chapter 4 (Brünenberg, Rummel and Trümper) and Chap. 12 (Kruse and Schönenberger) presented case studies which mainly relate to the documentation of archaeological contexts and the study of features. The study presented in Chap. 5 (Fouriaux) combines the documentation of archaeological contexts with the 3D documentation of artefacts, focusing on the complex relationships between objects in a 3D space, while basically adopting a 3D GIS approach. As highlighted in Chap. 3 (Innerhofer, Reuter and Coburger), the use of 3D archaeology helps in the study of surface features of objects, such as use traces or decorations. This is briefly mentioned in Chap. 12, but it is the focus of Chap. 6 (Horn et al.), which shows how 3D technology is transforming the study of rock art. In Chap. 7 (Trinkl et al.), several approaches to data collection, automated retrieval from databases and 3D feature analyses were presented, including a novel approach to unwrapping, while preserving the geometries of the unwrapped features. Analyses of spatial relationships and volumetric measurements, as well as surface analysis under exclusion of texture, which can only be done with difficulty when using traditional documentation techniques, can be conveniently carried out using digital 3D techniques.

In Chap. 8 (Opgenhaffen, Jeffra, Hilditch), a database to study the technology behind Aegean pottery was presented. It was created as a reference collection of 3D objects for both specialists and the general public. However, 3D objects cannot easily be displayed, as they require specialised viewers that often facing restrictions in upload quality. Similar challenges arose in the case study presented in Chap. 9 (Pendić et al.). Here, a collection of human remains was made publicly available. In addition to technical challenges, ethical considerations also need to be taken into account when determining the extent of access. The authors of Chap. 8 (Opgenhaffen, Jeffra, Hilditch) heavily stressed the importance of contextual information, which must be attached to any 3D object. Preserving the context is of critical importance for archaeological collections, and robust protocols must be used to ensure this. The challenges involved in providing access to the general public and specialist audiences were taken up on an overarching level in Chap. 10 (Fernie), where pressing problems, such as a lack of metadata, standardisation and interoperability, became apparent. Novel approaches to the multi-modal retrieval of different kinds of digital archaeological objects were presented in Chap. 7 (Trinkl et al.), while the relevance of long-term archiving was particularly emphasised in Chap. 10 (Fernie) and Chap. 12 (Kruse and Schönenberger).

In Chap. 12, the aim was to establish a smooth and sustainable workflow for the archiving of 3D datasets generated in everyday (rescue) archaeological work. Here, the capacity for the long-term archiving of digital 3D datasets is understood as the precondition for fully incorporating the methods into everyday workflows. This broad spectrum of topics and approaches is reflected in the results of the survey on the application of 3D technology in archaeology presented in Chap. 11 (Hostettler et al.). Among other observations, the survey revealed that female practitioners are apparently underrepresented in the field of 3D archaeology.

Despite intensified efforts on various levels and within large-scale projects to tackle challenges such as a lack of open-source applications, interoperability and solutions for long-term archiving, most of these issues remain unresolved. These problems are pressing and lie at the heart of responsible research in archaeology. Despite growing talk of 'de-collecting' (Hofmann et al. 2016), it is important to acknowledge that archaeological practice destroys its own primary sources. It is the context of retrieved archaeological objects that, in essence, gives value to what are otherwise merely old things. Just as the most precise radiocarbon date loses its value when its context is unclear, archaeological 3D objects become worthless when their context is lost. Thus, as Kruse & Schönenberger put it in Chap. 12, if 3D technology is to be considered as established in archaeology, long-term archiving needs to be ensured.

As Bridle (2018) and Kucklick (2015) have argued, the digital age can be characterised by the fundamental idea that everything can be quantified. Computers are the most important tool of this era, but their use gives rise to other, deeper challenges.

In the introduction to his book *Die granulare Gesellschaft,* Kucklick gives the example of a child with a grave illness (diabetes) who has the possibility to receive a tailored therapy thanks to the comprehensive data collection that can be performed on their body using highly sensitive electronic devices. From there, Kucklick develops the idea of a granular society (*granulare Gesellschaft*), in which high-resolution datasets replace the dominance of mean and average values – such as the monitoring of diabetes via mean blood sugar values – in our understanding of the world. In *New Dark Age,* Bridle (2018) notes that there is an increasing lack of understanding in our society concerning the growing amount of information that is widely available and that continues to be produced on an unprecedented scale. He also observes growing complexity and a growing dependence on large-scale infrastructure. Moreover, while the digital manifests itself within material objects and a physical realm (e.g. computers, drones, server farms, etc.), its contents increasingly seem to lack spatiality. Spatiality again is an essential property of what we understand as the physical world, and its absence thus lies completely beyond our experience as biological subjects.

As can be seen from many examples presented in this book, these notions are inherently true for the use of 3D technology in archaeology: when 3D models are produced, more data on the objects under study is generated, which can lead to new results. Moreover, another dimension of these new possibilities is the ability of the digital object to be accessible beyond geographical boundaries (once the infrastructure has been put in place). These properties once again underline the fundamental importance of context being preserved and strategies being formulated to structure the new masses of data in meaningful ways. Approaches that go in this direction have been presented in this book.

That said, technology and infrastructure are also implicated in problematic and violent contexts. Access to much of the needed infrastructure is regulated by (economic) power relations. The infrastructure itself is built using materials that are often mined in exploitative contexts by imperialistic agents. This violence inherent in modern technology should not be ignored, either on the societal level or in archaeology. The entanglement of modern technology with warfare and exploitation has been underlined in a polemical way by Hutchings (2014), who sharply attacks the uncritical embrace of technology by the organisers of a public event on digital archaeology. This entanglement may also be exemplified by Bridle (2012), whose artwork depicts the outlines of military drones on public grounds and thus tries to bridge the uncanny gap between their destructive purpose and their base of operation.

However, it is not only technology that is entangled in violence and warfare, but also archaeology as a discipline. The deliberate destruction of cultural heritage during the civil war in Syria garnered widespread public attention, and it was argued that the attacks explicitly targeted the ‘West’ and its institutions. Although 3D technology was feted as a countermeasure to the large-scale destruction in Palmyra, it failed to address the suffering of the civilian populations involved (for a discussion and further literature, see the debate carried out in *Archaeological Dialogues* in 2020: Meskell 2020; Rico 2020; Stobiecka 2020a, b). However, this debate also revealed a deeper history of violence surrounding Palmyra: the city was cleared of its inhabitants in the early twentieth century to enable the archaeological study of its ancient remains (Meskell 2020). A broad discussion of ethics in digital archaeology is still missing, although some efforts have been made (Khunti 2018; Dennis 2020).

In light of these ethical failures, it seems necessary not just to ‘absorb’ (Morgan 2022, p. 224) new technologies into common practice, but also to adopt a much more critical approach towards digital archaeology, one that considers the broader societal implications of technology (see also Caraher 2019). As Morgan (2022), p. 225, puts it: ‘Digital work within archaeology must move beyond skeuomorphic submission and replication of previous structural inequalities to foment new archaeological imaginaries.’ In a digital world, it is of fundamental importance to maintain awareness of these issues, as the violence is not readily visible or displayable (e.g. in the case of drones). Accessibility also goes beyond digital barriers, and access to digital infrastructure cannot be taken for granted. This is true not only in a geopolitical sense, but also with regard to future generations. The accessibility of our common heritage, to which archaeological objects inherently belong, must be guaranteed in a global and sustainable way. Infrastructure is of fundamental importance here, and archaeology must inform political decision-making in this regard.

Finally, the computational nature of digital 3D objects must be acknowledged. These objects represent the translation of the archaeological record into high-resolution datasets. This data might allow completely new narratives and understandings of the past that move beyond sweeping trends or rough classifications. As was attempted in this book and as is demonstrated by its authors, 3D archaeology can augment the ontological and analytical toolset available in the field. Moreover, we are currently working on strategies to ensure the preservation of the digital record in the long term. Where this might lead us and whether we are able to develop and pursue a sustainable and ethical digital archaeology remains to be discussed in the years to come. Large-scale databases structuring different kinds of archaeological data (e.g. radiocarbon, 3D objects, palaeoecological datasets) and new computational ways of understanding them seem to represent only the first steps towards revolutionising archaeology.

References

Bridle J (2012) Drone shadow 001–009. https://jamesbridle.com/works/category:drone

Bridle J (2018) New dark age. Technology and the end of the future. Verso, London/Brooklyn

Caraher W (2019) Slow archaeology, punk archaeology, and the 'archaeology of care'. Eur J Archaeol 22:372–385. https://doi.org/10.1017/eaa.2019.15

Dennis LM (2020) Digital archaeological ethics: successes and failures in disciplinary attention. J Comput Appl Archaeol 3:210–218. https://doi.org/10.5334/jcaa.24

Hofmann KP, Meier T, Mölders D, Schreiber S (eds) (2016) Massendinghaltung in der Archäologie: der material turn und die Ur- und Frühgeschichte. Sidestone Press, Leiden

Hutchings R (2014) Weapons of mass destruction: UBC archaeology day, digital technology, and the rapidly spiraling scientification of humanity. Inst Crit Herit Tour Bull 2014

Khunti R (2018) The problem with printing Palmyra: exploring the ethics of using 3D printing technology to reconstruct heritage. Stud Digit Herit 2:1–12. https://doi.org/10.14434/sdh.v2i1.24590

Kucklick C (2015) Die granulare Gesellschaft: wie das Digitale unsere Wirklichkeit auflöst. 2. Aufl. Ullstein, Berlin

Meskell L (2020) Hijacking ISIS. Digital imperialism and salvage politics. Archaeol Dialogues 27:126–128. https://doi.org/10.1017/S1380203820000252

Morgan C (2022) Current digital archaeology. Annu Rev Anthropol 51:213–231. https://doi.org/10.1146/annurev-anthro-041320-114101

Rico T (2020) The second coming of Palmyra. A technological prison. Archaeol Dialogues 27:125–126. https://doi.org/10.1017/S1380203820000240

Stobiecka M (2020a) Archaeological heritage in the age of digital colonialism. Archaeol Dialogues 27:113–125. https://doi.org/10.1017/S1380203820000239

Stobiecka M (2020b) 'Violent care'? A response to Lynn Meskell and Trinidad Rico. Archaeol Dialogues 27:128–134. https://doi.org/10.1017/S1380203820000264