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Research Article

Photogrammetry and 3D modelling in university teaching. A case study applied to the history degree

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Abstract

The aim of this contribution is to provide a new methodology regarding the use of photogrammetry and 3D modelling in the classroom. By means of a *practicum* taught at Complutense University of Madrid and a survey conducted afterwards, we show the different steps of the activity, as well as the reception of the students, who learnt to elaborate 3D figures.

Keywords: Photogrammetry, 3D modelling, Digital Humanities, heritage, Metashape, Blender, Ultimaker Cura

Introduction

This paper aims to provide a practical approach to a branch of Classics teaching that is not often applied, i.e. using archaeological artifacts to learn about the material culture of Antiquity through photogrammetry and 3D modelling. This contribution will show a case study undertaken at the Complutense University of Madrid (Spain) during the first semester of the 2022–2023 academic year. The objective was to train students in creating 3D figures of archaeological artifacts,[1] as a way to improve both their digital competence and their knowledge about the material culture of ancient civilisations, as well as to create an innovative and stimulating environment in the classroom.

This activity is part of a major project entitled *Experimenta la Antigüedad Digital* (*Experimenting Digital Antiquity*) undertaken at the same university in the previous academic year (2021–2022).[2] It consisted of the creation of both a virtual and a physical collection of 3D archaeological materials for educational purposes. The initiative was possible thanks to a collaboration with the National Archaeological Museum of Spain and the Royal Academy of Fine Arts of San Fernando, as well as a group of 30 students that took part in the project.[3] The Department of Prehistory, Ancient History and Archaeology currently has a compilation of 20 figures, all of them from Greek and Roman contexts.

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Aware of the potential of photogrammetry and 3D modelling for teaching the Classics, we decided to organise a more specific activity in the four-session *practicum* of a course. Our purpose was clear: it was for every student to learn to work with archaeological artifacts and make 3D copies.

What is photogrammetry and what is its use in the human sciences?

Photogrammetry is the science of using photographs or 2D images to produce 3D models to acquire accurate measurements of a landscape, infrastructure or object with a defined and determined volume. This discipline emerged in the 19th century thanks to the invention of photography and its application in the sciences of cartography and topography.[4]

The science of photogrammetry has gone through a number of different techniques to produce its 3D models. The first major steps were the intersection of different images for cartographic measurement and their 3D surveying employed by Aimé Laussedat in 1851[5], Albercht Von Meydenbauer's 1858 invention of the stereoscopic camera to take measurements on photographs of buildings[6] and the development of the first stereoscopic instrument for vector mapping in 1896 thanks to the surveyors Edouard Deville and Eduard Gaston (El-Brahim, 2016, p. 5). Other major advances were the double projection in images by Captain Theodor Scheimpflug and his instrument for rectifying the optics of photography in 1903 and Carl Pulfrich's 3D stereoscopic vision in relief[7]. With the establishment of the International Society of Photogrammetry in 1910 and the holding of its first congress, the foundations of the analogue system of photogrammetry were laid (Marín-Buzón *et al.*, 2021, p. 2). This new form of image acquisition and measurement was the precedent for today's photogrammetry, whose differences lie in the way the calculations are made and the superposition of images[8]. With the advent of the electronic computer, calculations became automated, facilitating the processing of information for improvement. This situation has accelerated in the digital era, and the development of different computer software to calculate the whole process of capturing and constructing information has turned photogrammetry into a worldwide science[9].

The application of photogrammetric science in archaeology is attested since the 19th century. Its function was not only to document, but also to protect heritage from possible destruction. An example of this was the establishment of the Royal Prussian Institute of Photogrammetry in 1885 aimed at creating a documented monument archive of endangered cultural and natural heritage (Foramitti, 1976). Photogrammetry made it possible to document sites for subsequent measurement in the laboratory work, as Karl Franz Stolze did in Persepolis and at the Mesdjid-e-Djumä Mosque (Persia) in 1874 (Albertz, 2001, p. 21). In more recent times, the formalisation in 1964 of the International Charter on the Conservation and Restoration of Monuments and Sites led to the creation of the International Committee for Architectural Photogrammetry, in which archaeological work was included[10]. Today, thanks to technological advances, photogrammetry applied to archaeology uses many techniques and instruments[11], such as laser technology and 3D scanners, together with high-resolution cameras, to document, preserve and analyse archaeological or artistic materials[12].

Benefits of teaching photogrammetry in a Classics context

Photogrammetry, as well as 3D printing, are nowadays a firmly established teaching resource in several branches of knowledge, most frequently in science,[13] but also in the humanities. This applies not only to the university, but also at all school levels, where this richness can bring enormous benefits to project-based learning (PBL). Besides, costs are becoming increasingly affordable, making these techniques easier to use (Blázquez-Tobías *et al*., 2018, pp. 164–173).

Two examples can reflect the usefulness to this technology. In 2017 a school in Bogotá, Colombia, inaugurated a 3D printing lab where pre-school, primary and secondary school students developed design and 3D printing projects that allowed them to reinforce the learning objectives of different subjects: music, biology, history, mathematics and physics (De la Cruz Campos *et al*., 2022, p. 74). There are also specific applications in the field of history and archaeology. A project undertaken in Afghanistan by the Oriental Institute of Chicago University is worth mentioning. One of the activities of the aforementioned project consisted of creating a 3D printed collection of the finds kept at the National Museum of Afghanistan, and visiting schools – focusing on those for women and girls – to teach them about their own heritage and past using those artifacts, among other resources. In other words, they bring the museum to the classroom (Stein, 2019).

Considering the potential of photogrammetry in history and archaeology studies, we decided to focus on the pedagogic and didactic benefits of its application in university teaching of subjects related to the study of Classical Antiquity aiming not only to work with the physical artifacts, but also the process of undertaking the photogrammetry. To a certain extent, these benefits can be linked to those of a self-regulated learning (SRL) activity, as defined by both Zimmerman (1986, 1989) and Huber (1997, 2008).[14] The former developed the socio-cognitive theory in which individuals acquire knowledge by observing others and the social interaction of the classroom.[15]

SRL is based on different phases: (1) Observation, in which the student sees the activity, introducing him/herself to photogrammetry and seeking information about the specific material; (2) Emulation, by repeating the tasks of the teacher/specialist and searching for the corresponding information, subsequently creating the photographs that will end up forming part of the 3D model the student will make; (3) Self-monitoring, consisting of being able to measure their own skills and filling the gaps both in the knowledge of the artifact and the photogrammetric development by comparing the progress of their study with that of the teacher/specialist; (4) Self-regulation, in which the students are competent in their skills and are able to adapt to overcoming difficulties in the development of their activity.

This learning system has benefits related to the didactics of the object, since the student learns by manipulating the artifact in a more immersive way.[16] In the case of the application of photogrammetry we find two ways of learning related to this teaching methodology. The first is active, i.e. the student learns by manipulating the artifact, both physically and virtually, observing its characteristics and linking them to the explanation given by the teacher. As Sweetman and Hadfield concluded in a project concerning the use and digitalisation of the Bridge Collection, which was donated to the University of St Andrews, to see and to feel artifacts in handling sessions had more potential and benefits than the traditional access to these materials. For example, there is a stronger connection with the craftspeople responsible, sparking the imagination to think about the object itself, its decoration, meaning and function (Sweetman and Hadfield, 2018, pp. 55–57). The second way of learning is passive, i.e. to carry out the entire photogrammetric process, thus acquiring historical knowledge by being involved in the processes of digitalisation and printing of the material. The students learn about the historical context and related issues of the artifacts they work with.

In addition, by adapting the teaching method, the application of virtualised objects and their subsequent 3D printing allows access to knowledge for students with visual disabilities (Aguirre Barco *et al*., 2002). The reproduction of the object and its subsequent manipulation breaks down these barriers and facilitates the acquisition of knowledge through touch. Likewise, benefits are observed in terms of knowledge accessibility for those with limited resources, as it offers the opportunity to manipulate the virtualisation or printing of artifacts from international museums without the barrier of distance.

Case study

Methodology

The case study shown in this paper was part of the *practicum* of the course *Ancient History I: Egypt and the Near East*. It is a compulsory subject for second-year history degree students. The number of enrolled students is higher than in courses belonging to the specialisation itineraries within this degree, such as Ancient History. Specifically, a total of 81 students attended the classes. They were divided into three groups with 27 individuals in each. The *practicum* calendar was organised around these three groups, i.e. each had its own four sessions. Each session lasted three hours.

The *Experimenting Digital Antiquity* project consisted of undertaking the photogrammetry of an archaeological object and its 3D modelling and 3D printing. However, for the purposes and nature of the *practicum* of the course explained here, the last step was not feasible. Due to the large number of students, 3D printing was not possible for each of them.[17] This final phase was therefore adapted according to the characteristics and determinants of the course *practicum*.

For the task of taking pictures, the students were able to use cameras or mobile phones, whose quality today is sufficient to obtain accurate photographs for a non-professional activity. Students were required to use their own laptops or personal computers for 3D modelling.[18] Tablets were not allowed as they cannot run the software.

The case study included the use of three computer programs for different phases of the 3D modelling. The first was Metashape,[19] which processes the pictures of the archaeological artifact and creates the 3D model; the second was Blender, for minor corrections and specific additions; and the third, Ultimaker Cura for learning how to establish the printing parameters according to the 3D printer type and to export the 3D figure in a format that makes it possible to be printed.[20]

Development

First session

The purpose of the initial session of the *practicum* was to undertake the photogrammetry of an archaeological artifact. It was first necessary to explain the meaning and functions of photogrammetry, as well as the development of the technique from its inception, focusing the description on historical and archaeological studies.

Next, as a way of seeing the complete process of the *practicum*, the students were able to observe the collection of 3D-printed finds created by the *Experimenting Digital Antiquity* project and to touch and handle the objects. The aim of this part was to increase their interest in the activity, as well as to show them the features of artifacts and to explain them their historical context.

The following section of the session consisted of carrying out the photogrammetry. The teacher, Diego Chapinal-Heras, provided a compilation of figurines related to the Egyptian culture, primarily an *ushabti* and votives of Hathor, Osiris, Amun and Nekhbet.[21] The students were organised into pairs to allow each of them to take the pictures. They worked with the finds in turn. The teacher was always available to answer any questions and resolve any situations that arose.

The activity took place in a normal classroom at the Faculty of Geography and History, meaning that the lighting of the room was somewhat deficient. In order to correct this problem, one of the students of each pair took the photographs while their partner used the torch function on a mobile phone to illuminate the surface of the archaeological object. This notably improved the quality of the photogrammetry.

Second session

The entire content of the second part of the *practicum* dealt with the use of software for 3D modelling (Figures 1, 2 and 3). The programs chosen for this task were Metashape and Blender. Students were required to attend the class with their laptops.

Prior to the activity, it was necessary to download and install the software following the instructions provided by the teacher in the Virtual Campus (Moodle). They also created a folder in their virtual desktop in which to store the images from the photogrammetry. That folder was used during the *practicum* to store the 3D model archives and other data generated throughout the process.

Starting with Metashape, the students transferred the photographs to the program and followed the steps that lead to the creation of the 3D model. The time spent on this task varied, depending primarily on the quality of the computer each student used. Any delay was resolved by explaining the different concepts of photogrammetry and discussing the potential of photogrammetry and 3D modelling in history and archaeology studies. Some of the students, for example, were interested in the use of photogrammetry in excavations, as well as in the job market. It was concluded that having this kind of knowledge increased the chances of getting a job in the humanities. It was also often necessary to resolve doubts and deal with unexpected situations. The final step with Metashape

Figure 1. Second session, using software for 3D modelling. @ Carlos Díaz-Sánchez.

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Figure 2. Second session, using software for 3D modelling. @ Carlos Díaz-Sánchez.

consisted of exporting the 3D figure files in .obj and .stl formats, those most commonly used for visualisation and the further application of changes with other software.

The reason for the use of Blender was two-fold. On the one hand, it provides tools to correct minor errors and flaws in the 3D figure, such as holes or sections of the surface that might be rough. On the other hand, students were trained to be able to place the 3D model on pedestals or similar types of support. In this way, the activity recreates the preparation of a 3D figure for a virtual exhibition.

In terms of the development of the session, teaching how to use Metashape was more time-consuming than the explanation of Blender. The main reason was, as already explained, that some steps of the 3D modelling process required more time, especially when the laptops used by the students worked too slowly. Despite this challenge, a three-hour session was enough to teach the basic aspects of both Metashape and Blender.

Learning to use this kind of software might sometimes seem stifling or overwhelming, especially when the level of IT knowledge

Figure 3. Second session, using software for 3D modelling. @ Carlos Díaz-Sánchez.

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is low. In order to avoid situations in which students become stressed or believe that they will be unable to fulfil the task, the teacher prepared two video tutorials that summarised the instructions for the proper use of Metashape and Blender. They were recorded using the open-source program OBS Studio and edited with CyberLink PowerDirector 365, also free. Once edited, both videos were uploaded to the Virtual Campus after the session, so that students could revise the tasks.

Third session

The main topic of the third part of the *practicum* was the use of Ultimaker Cura. This software allows a 3D model figure in .stl format to be transformed into a 3D-printable file according to the specific requirements of each printer. As in the previous session, the students had already downloaded and installed the software on their laptops. During the class, they learned how to set the printing parameters of the 3D printer they would hypothetically use. The printer chosen as an example was the one used in the *Experimenting Digital Antiquity* project, a Creality Ender 3. The students followed the instructions and, once they had finished the task, exported the 3D model in a gcode format archive recognised by 3D printers (Figure 4).

Since accurate work with Ultimaker Cura requires setting up a wide range of specific parameters, the teacher prepared another video tutorial. The students could therefore go over the explanation and check if they had proceeded properly.

Teaching how to use Ultimaker Cura took approximately half the session. For the second half, the activity chosen was to show the resources available on the internet regarding 3D modelling in history and archaeology. The purpose of this section of the *practicum* was to make students aware of the potential of this new technology in their field, as the following lines will show.

The explanation was divided into two parts. First, the students learned about the main virtual repositories for 3D models, especially those focused on history and archaeology. These websites are Sketchfab[22], Thingiverse[23], Myminifactory[24], Pinshape[25] and Cults3d.[26] All these repositories offer the possibility of downloading 3D models – some free and other not, depending on each case – as well as uploading their own archives. As a way of making this part more interactive for the students, they were able to refer to archaeological sites or finds related to the contents of the course and check if they were available as 3D models on these websites.

The second part was an overview of specific applications in the sphere of the Egyptian and Near Eastern civilisations. It is worth mentioning that among these territories the major advances in terms of virtualisation have been in the field of the Nile culture. The main reason could be that Egypt has traditionally awakened more interest in both the scholarly and public spheres, whereas the Near East is seen as secondary. The unstable political situation of some countries, such as Iraq and Syria, has also hindered new developments in those regions[27]. The exhibition began with the virtual tour of the archaeological area of Giza offered by Harvard University.[28] Other relevant resources for Egyptian materials are the section housing the Tutankhamon Treasure in the Egyptian Museum of El Cairo[29]; a short selection of tombs[30]; and the Egyptian collection at the National Archaeological Museum of Spain.[31] With respect to the Near East, some of the cases seen in the classroom show the enormous usefulness of 3D reconstruction in preserving the memory of sites and materials that may suffer or have suffered damage due to current political dynamics.[32] In this sense, the students were able to see the augmented virtual reality work that Yale University has carried out in the Northwestern Palace of Nimrud (Iraq),[33] as well as a 360° tour of Palmyra[34]. Another valuable source is the *Endangered Archaeology in the Middle East and North Africa* (*EAMENA*) Project, which aims to record and evaluate the status of the archaeological sites of these regions in order to create an accessible body of data that can be

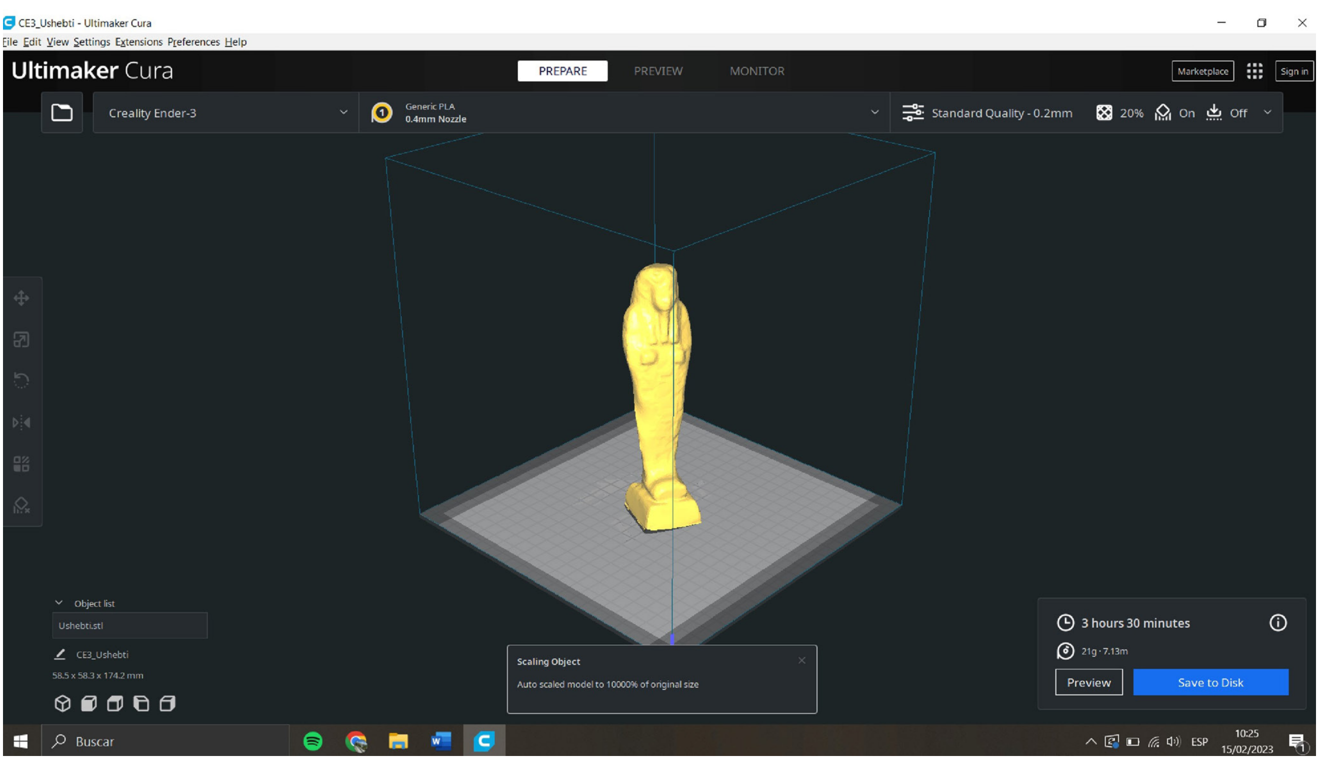

Figure 4. Example of 3D figure (ushebti) in Ultimaker Cura.

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used by heritage professionals to target those places that require more attention and protection.[35]

Fourth session

The final session of the *practicum* consisted of a 3D printing demonstration. Thanks to the fact that the Creality Ender 3D is easily portable, it was possible to carry it to the classroom. Initially, the teacher gave a brief explanation of the components and main settings of the printer. Afterwards, the device was activated and began to print one of the figures the students had worked with. The size of the 3D model was adapted to the time available for the session, i.e. a maximum of three hours.

While the printing was in process, the teacher organised an activity to expand the students' knowledge of 3D modelling. It required them to use their mobile phones to download and install the EyesCloud app. This program was chosen because it is open-source, there is no charge for most of its functions and it is available for both Android smartphones and iPhones, meaning all the students were able to use it.[36] With this app it is possible to carry out the photogrammetry and 3D modelling of any object that a mobile phone can photograph or record on video.[37] The students were divided into pairs again and had to undertake the photogrammetry with their partners. This task increased the students' interest and showed them further applications of the technology.

Once the 3D printer had finished its work and the students had concluded their task with EyesCloud, the *practicum* ended with a raffle of the printed figurine.

Evaluation of the activity

The homework that the students had to submit was specified in class in the first session and in a document uploaded to the Virtual Campus. They were told to send three pictures of the photogrammetry, the textures generated by the 3D modelling software and the 3D figure in .obj, .stl and .gcode formats. In this way it was possible to examine the entire process of the photogrammetry and 3D modelling task. The results were satisfactory. All the students that attended the class regularly were able to create high- or medium-quality 3D figures.

Pedagogical analysis

Statistical analysis of the development of the practicum

In order to ascertain the opinions and results of the students' training, an anonymous voluntary survey was carried out to enable them to express their difficulties, shortcomings and level of satisfaction with the *practicum* (Supplementary Figures 1 and 2).

Within the total number of students who took the voluntary survey (11), the vast majority had little computer-related knowledge (Supplementary Figure 3).

Meanwhile, from the materials suggested for the development of the practice, it can be highlighted how in all cases the camera used was that of their mobile phone, processing the images on both laptop and desktop computers (Supplementary Figure 4). The overall satisfaction with the development of the internship is positive (Supplementary Figure 5. Table 1), although the follow-up of the internship has become somewhat complicated (Supplementary Figure 5. Table 2).

Finally, students' opinions of whether or not training in photogrammetry can be beneficial in both in their training as historians and their professional futures can be highlighted (Figure 5).

Engaging the students with Digital Antiquity

This activity was aimed at bringing students closer to the material culture of Antiquity by means of 3D modelling. There are currently

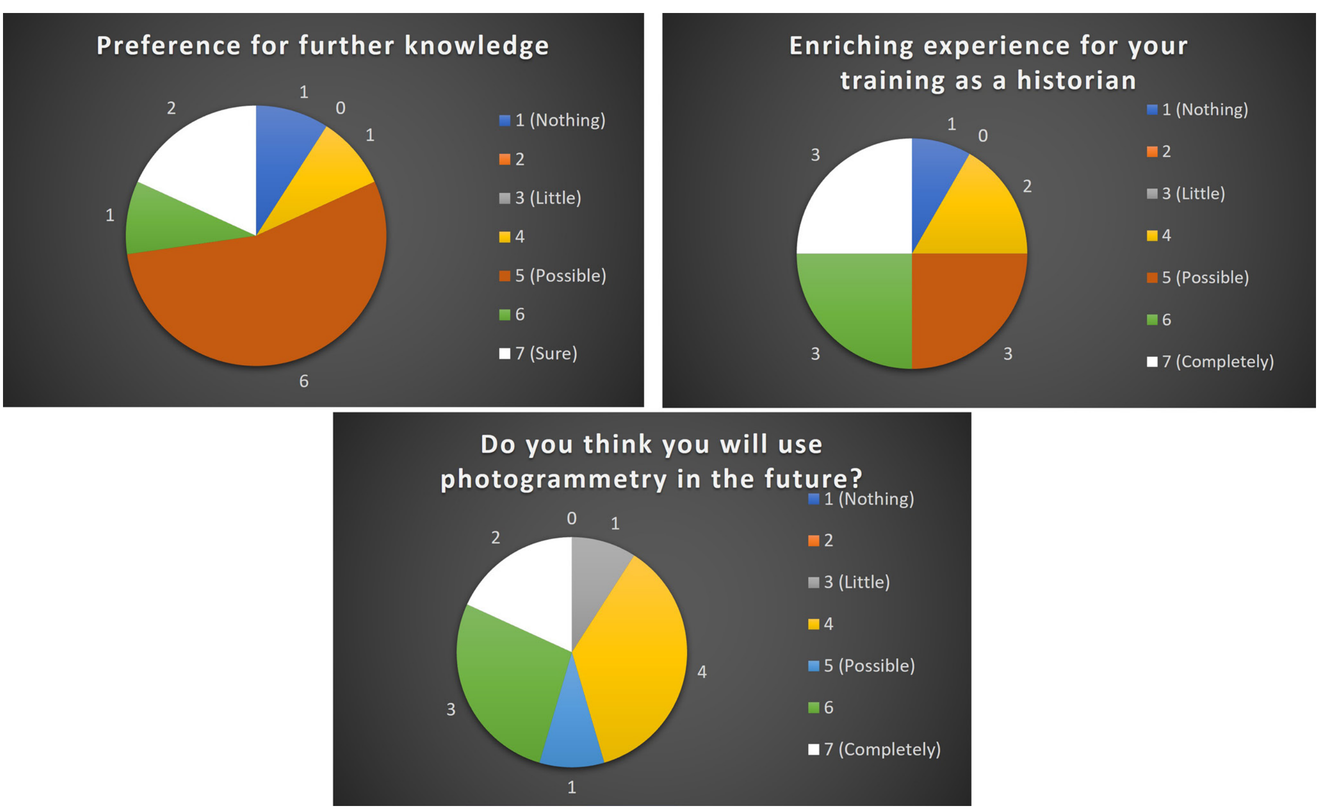

Figure 5. Opinion on the use of photogrammetry in your professional future.

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many ways to do this. Viewing illustrations in textbooks or on PowerPoint presentations is the easiest and most common method. The possibility of visiting museums or providing the students in the classroom with a brief selection of artifacts – originals or replicas – is also very useful. In this paper we propose a teaching methodology that combines all these possibilities while taking advantage of the major developments of the new technologies. 3D modelling is no longer an unreachable activity in the field of humanities for either teachers or students, as we attempt to demonstrate. This methodology is also valuable for the teacher because it offers a stimulating and interactive alternative way to engage students with the contents of their subject. Rather than replacing other more conventional educational practices, what we are proposing is intended to be an extension, a complement. The use of this technology requires a detailed explanation of the ancient materials being used, while offering an innovative way of working with them.

Throughout the *practicum*, the students are able see physical replicas of ancient figurines, take pictures of them and carefully proceed to make 3D models. The process involves examining and analysing a variety of features and characteristics of the artifacts, thus giving them a more in-depth knowledge of these resources from the past. Carrying out this series of tasks helps the students to obtain significant learning based on experimentation, which leads to an increase in motivation that improves their educational results. They have fun at the same time as they experience and learn, thus generating a desire to continue acquiring knowledge that they themselves know will be useful, not only for the present, but also for the near future, both personally and in the job market (Blázquez-Tobías *et al*., 2018, p. 176).

In the light of the results obtained throughout the development of the *practicum*, it is useful to look in greater depth at the pros and cons of carrying out such an activity within the framework of university teaching. First of all, we will set out a list of advantages and disadvantages of this particular case study and then move on to broaden the explanation of each point.

Advantages:

- Improving students' digital skills
- Knowledge can be applied to different fields
- Good ratio of 3D modelling process/course duration

Disadvantages:

- Lack of suitable tools (such as computers, powerful enough GPUs)
- Lack of digital skills

Above all, the great perk of such an activity is the development and strengthening of the students' digital skills. Teaching-learning processes are here understood as makerspaces, i.e., construction and creation spaces where the digital aspect is of particular importance (De la Cruz Campos *et al*., 2022, p. 69). At the same time, they acquire a better and deeper knowledge of the historical context of the artifacts, their functions and meaning. We can see the importance of an interdisciplinary approach to different areas. This knowledge provides the students with an ability that can be useful in their training as historians and for their professional futures. As stated previously in this paper, the knowledge of photogrammetry and 3D modelling is a compelling asset. This type of skill is not yet widely included in humanities programmes and therefore this experience differentiates them from other professionals and not only increases the scope of their education and overall training but also affords them better job opportunities.

Another advantage in this respect is the potential possibilities this digital skill offers. Having been instructed in 3D modelling, the students can apply this knowledge to their chosen area of expertise. As we have seen from this particular case study, the activity involved working with Egyptian and Near Eastern archaeological materials. However, it could also be carried out with a wide variety of archaeological materials or finds from different periods or locations, including, obviously, Classical Antiquity. Finally, this four-session *practicum* was also very convenient in terms of the time needed, as it was possible to conduct all the phases of the photogrammetry and 3D modelling process, while, at the same time, giving plenty of time for the students to interiorise the information provided and to answer their questions.

Regarding the disadvantages, the greatest was the possible digital gap between students. As previously stated through the polls, most of them had few computer skills prior to this activity. Despite being "digital natives", their knowledge of certain IT software was limited. As UNESCO explains, digital competence is acquired through a three-step process: first, digital literacy, so students use this technology more efficiently; second, deepening knowledge, which allows them to better expand their knowledge of the different disciplinary fields; and a third phase of knowledge creation, in which the efficient use of technology allows the creation of new knowledge from the previous one (Gisbert Cervera *et al*., 2016, p. 76). To overcome this challenge the teacher's guidance and explanations are necessary the entire time. This situation was also solved by providing pre-session video-tutorials on how to use the software. This allowed the students to revise at home the explanations on 3D modelling. The occurrence of errors throughout the work with the 3D modelling software, due to both the lack of digital skills and technical issues with the program, allowed the teacher to give more in-depth explanations on how the software functioned and, therefore, guide the students into solving whatever problems they may encounter in the future.

The other issue at hand was the lack of suitable equipment to carry out the activity. Many students did not have laptops able to run the software adequately. This was solved by pairing the students, allowing them to work collaboratively with one another and satisfactorily follow the sessions. Among the students' laptops that could run the software, there were a few that worked quite slowly, thus delaying the process. The teacher took advantage of the delay by engaging the students in a debate on the uses and applications of 3D modelling, in order to broaden their understanding of the subject in hand while waiting for the software to finish the different steps of the process.

A third aspect to take into account is the number of participants in the *practicum*. Although the 81 students were divided into three groups of 27 each, this may still be too many. In some steps of the process, it was necessary to solve the problems of many students at the same time. Therefore, the application of this *practicum* in a class with fewer students, or with the support of a teaching assistant, would certainly make the activity easier to handle.

The disadvantages, although not insurmountable, could potentially delay and prevent the students from completing the task and successfully finishing their homework. However, in our particular case, this did not happen, as all students were able to generate their 3D models. Hence, we found that the advantages greatly outweighed the possible disadvantages we faced throughout the course.

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As stated above, although this *practicum* was organised at a university, it is more than possible to undertake it at high school level. Photogrammetry and 3D printing as a teaching resource have already been applied and proved successful here. Whereas the explanations of the significance and functions of the materials employed should be adapted to the contents and schedule of each year of high school, the techniques and tasks required of the students are easily within their possibilities. Likewise, this is a practical activity that allows a stronger engagement with history and archaeology and, at the same time, provides basic notions of a sector, 3D modelling, that is currently applied in many fields. Therefore, it would benefit their learning and training in other areas of knowledge that are taught in high school.

Conclusions

The proposed case study increases specific skills in the field of the Classics, as well as enhancing the teaching methodology to offer a comprehensive transdisciplinary qualification that reinforces the training of students. It provides a holistic experience based on three areas of action: direct contact with the study objects, the handling of them in the digital environment; and finally, their reproduction. In short, this *practicum* explores the possibilities of teaching the materiality of artifacts from the past and training the students to create 3D models of them using different techniques and software. The benefits of this activity lie in achieving closer and more personal contact with the material culture. While learning how to make 3D models, students learn about the historical context, meaning and functions of the artifacts. They come to perceive how these objects are related to the culture to which they belong. Likewise, the creation of digital models overcomes some of the disadvantages of physical and original ones, such as breakage. In the same way, the fact of having the model in digital format makes it possible to disseminate it (De la Cruz Campos *et al.*, 2022, p. 69).

The proposed methodology brings new life to materials beyond their traditional function as museum pieces or works of art. In fact, museums have led the way in using digital media, particularly 3D reconstructions and including on-line access, to better place the materials on display in their historical and cultural context (Sweetman and Hadfield, 2018, pp. 49–50). Breaking down this barrier allows both teachers and students not only to understand the past, but also to intervene in heritage and – according to Riegl – give it a contemporary value. The main purpose has been to train students in 3D modelling, as a means of establishing a close connection between them and the material culture of the ancient civilisations they study. From here, the possibility of printing the results opens up, thus providing the classroom with materials and bringing the benefits mentioned throughout the paper and which are inherent to the handling of archaeological pieces. In this sense, this case study and its potential further applications are likely to be projected into the future, as the proposed methodology is easy to apply in more contexts, in both university and high school, thanks to its flexibility and attractiveness for students.

Supplementary material

The supplementary material for this article can be found at https://doi.org/10.1017/S2058631023000429.

Notes

1 It is worth mentioning that this activity can be applied at high school level. In this respect, in the near future we will present the results of another case study in which we organised a training session for students in the second year of ESO (ca. 13–14 years old).

2 2021 Innova-Docencia Call, Complutense University of Madrid. Code PIMCD 2021, No. 361.

3 A preliminary report of the project is published in Chapinal-Heras *et al.* (2023).

4 Authors such as Gosh (1981) and Von Brevern (2011, p. 27) explain how the artistic perspective developed during the Renaissance may be a precedent for the sensation of three-dimensionality generated by photogrammetry.

5 On the analysis and technique employed by Colonel Aimé Laussedat see: Albertz (2007, pp. 504–506) and Von Breverm (2011, p. 57).

6 This camera innovation was made possible by physical advances in Ernst Mach's stereoscope that allowed volumetric measurement through two-dimensional images. See: Albertz (2001) and El-Brahim (2016, p. 5).

7 Scheimpflug was also the first person to apply photogrammetric principles to aerial photography, generating three-dimensional planes of the landscape. See: Bervoets (1969, pp. 529–540).

8 The technique of analogue photogrammetry consisted of numerical measurement and evaluation by means of a printing and graphic design machine that generated a stereomodel of the object using mechanical optical relative orientation. See: Sanjib (1988) and Karara (1989).

9 On the evolution of photogrammetry in the digital era, see Pérez *et al.* (2014, pp. 108–124), Gonizzi Barsanti *et al.* (2013, p. 146), Marín-Buzón *et al.* (2021, p. 2), Clement *et al.* (2012, pp. 314–325), Clement *et al.* (2013, pp. 75–81), Galeazzi (2016) and Sapirstein and Murray (2017).

10 https://www.icomos.org/images/DOCUMENTS/Charters/venice_sp.pdf (accessed 1 February 2023).

11 On the tools and techniques used by archaeological photogrammetry today, see: Karara (1989), Brown and Dold (1995), Bewley (2003), Tsioukas *et al.* (2004), Obdahe and Chikatsu (2004), Bohm (2005), Alshawabkeh (2005), Bujakiewicz *et al.* (2006, p. 60), Guidi and Remondino (2012) and Tucci *et al.* (2017).

12 Examples are the reconstructions of the Roman town of Palmyra (Syria) (Denker, 2017), the restoration of the theatre of Byblos (Lebanon) (Younes *et al.*, 2017) and the accessibility of sites such as Ulaca (Spain) (Maté-González *et al.*, 2021; Rodríguez-Hernández *et al.*, 2023).

13 For example, printing molecules and related contents, as showed in De la Cruz Campos *et al.* (2022).

14 See the different models of SLR in Panadero (2017).

15 An approached nuanced in later publications: Zimmerman (2013).

16 On the didactics of the object see: Cardona and Feliú (2014), Prats and Santacana (2015, p. 19), Pinto (2018, p. 177) and Sweetman and Hadfield (2018) (dealing also with the concepts "art" and "artifact").

17 Printing a small figurine, e.g. a 10-cm-tall votive offering, requires between 3 and 5 hours.

18 If any of the students does not have one or any of these devices, a possible solution is to use the informatic equipment of the school or university, or that students who do have a laptop or personal computer share it with their classmates who do not.

19 Since there was no funding for this activity, the possibility of obtaining an official Metashape account for each student was ruled out. For this reason, we used the 30-day trial version. Originally, our aim was to train the students with licence-free software. However, Meshroom, the main program for this purpose, requires a very advanced processor and graphics card and most of the laptops students use for attending classes cannot support such demanding software.

20 Both Blender and Ultimaker Cura are licence-free software.

21 The finds were generously supplied by Prof. José Ramón Pérez-Accino Picatoste, Egyptologist at the Department of Prehistory, Ancient History and Archaeology at the Complutense University of Madrid.

22 https://sketchfab.com/feed (accessed 1 January 2023; all the links posted below were visited on the same date).

23 https://www.thingiverse.com.

24 https://www.myminifactory.com.

25 https://pinshape.com.

26 https://cults3d.com.

27 In this sense, a specific application of this sort of content in a class focused on Greece and Rome would certainly benefit from the plethora of digital resources that are currently available. http://giza.fas.harvard.edu/giza3d (accessed 1 February 2023).

28 http://giza.fas.harvard.edu/giza3d (accessed 1 February 2023).

29 https://my.matterport.com/show/?m=85n8j312Ur4 (accessed 1 February 2023).

30 Theban tombs 286 and 159 (https://www.arce.org/theban-tombs-286-and-159) and the Tomb of Menna, from the 18th dynasty (https://www.arce.org/tomb-menna) (accessed 1 February 2023).

31 http://www.man.es/man/exposicion/manvirtual.html (accessed 1 February 2023).

32 3D technology is also an important resource for keeping intact that which cannot yet be analysed because the technology available today is too invasive.

33 https://news.yale.edu/2017/09/25/students-visit-lost-archaeological-treasure-virtual-reality (accessed 1 February 2023).

34 https://www.kaemena360.com/360/PalmyraTour/?startscene=0&startactions=lookat(21.96,-5.47,130.79,0,0) (accessed 1 February 2023).

35 https://eamena.org/ (accessed 21 April 2023).

36 In the event that not all students have a mobile phone, the most practical option is to pair up in order to share it.

37 Compared to the work undertaken with a laptop and the aforementioned software (Metashape and Blender), the EyesCloud results were of lower quality. However, it is still useful for the students to make them aware of the potential and possibilities they have in this field with just their mobile phones.

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