

SURVEY AND 3D MODELLING OF UNDERGROUND HERITAGE SPACES WITH COMPLEX GEOMETRY: SURFACE OPTIMISATION FOR ASSOCIATION WITH HBIM METHODOLOGY

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Abstract

The historic centres of many cities have interior underground cavities or empty spaces dating from different periods. This paper establishes guidelines for systematising and simplifying the collection of data from underground heritage spaces, with the ultimate aim of facilitating the management of the information obtained and encouraging the conservation and public appreciation of this type of heritage hidden beneath the surface of our cities. The case study selected is a Roman cistern belonging to the network of underground heritage structures in Carmona. The photogrammetric survey conducted presented an additional complexity due to the small size of the space and its underground location. As the next step in the research, a 3D model is created. Lastly, a set of optimised strategies specific is proposed to the unique nature of this type of heritage.

Keywords

Water supply, Roman city, photogrammetry, reverse engineering, heritage building information modelling (HBIM), digital preservation

1. Introduction

Heritage conservation, dissemination and promotion strategies have evolved considerably in recent years thanks to the use of digital technologies like photogrammetry and laser scanning, which in turn has led to advances in the digital preservation in heritage protection methodologies and their widespread implementation. (García-Molina et al., 2021)

A crucial step in the conservation of certain heritage elements is the creation of an accurate 3D model reflecting the actual reality of the object in question. Traditional survey techniques, based mainly on the use of triangulation obtain the measurements of a space, are efficient for elements with a simple geometry. However, they do not deliver the necessary precision in the case of many underground structures and spaces because the error margin is too high, rendering this method ineffective for heritage management and therefore calling for the use of more accurate techniques.

Point cloud surveys are increasingly used to capture data at archaeological sites and heritage buildings (Benavides López et al., 2020). These surveys can be conducted with photogrammetry

or 3D scanning. Each of these techniques has its own characteristics and applications, and the use of one or the other is determined according to the research objectives (Volk et al., 2014).

In line with current demands in the field of heritage documentation, it is also good practice to combine a detailed survey with the creation of an information model capable of storing and classifying the data captured from the heritage element. However, building information modelling (BIM) systems have hitherto focused on contemporary architecture, standardised construction solutions and simple geometries.

In the case of heritage elements with a unique construction or morphology, importing point clouds and, in particular, generating 3D models becomes excessively complex.

It is often necessary to use computer aided design (CAD) programs to create specific pieces of the model. These programs can generate surfaces with complex geometry that would be extremely difficult to model with BIM software.

In the case of heritage building management, BIM methodology has to be adapted to encompass in a generic model of the city or the emerging architecture all the available information to facilitate the conservation, protection and

dissemination of the heritage. This adaptation is usually called HBIM (heritage building information modelling) (Murphy et al., 2009), and investigates the conceptual and methodological parallels that ensure its compatibility with heritage architecture. Thus, HBIM can be defined as an interdisciplinary work methodology for the sustainable management of built cultural assets (Castellano Román & Pinto Puerto, 2019). Its objective is to coordinate and articulate all the information on the cultural asset in a digital information model in which all the agents involved in its management can participate.

2. Related research

In general, point cloud surveys are used in heritage management to obtain the measurements of historical buildings of different types and characteristics. (Angelini et al., 2017; Galli et al., 2019; Nocerino et al., 2014). When the search results are filtered and the spaces drilled into the earth are mapped, the number of case studies decreases significantly. However, there are certain investigations that provide useful data for the field of study. At the typological level, surveys have been conducted of Mediterranean silos in Valencia (Valls et al., 2015), of reconstructions of underground structures and fortifications from World War One in Trento, Italy, (Rodríguez González et al., 2015), and of Bronze Age caves in the Dordogne Valley, France (Burens et al., 2014)

In relation to data collection methodologies for heritage, some interesting research compares the results obtained from point clouds according to the technical characteristics of the photographic equipment used, analysing the error and implementation margins in each case (Alessandri et al., 2020; Chikatsu & Takahashi, 2009). Studies have also been conducted on the use of a traditional photogrammetric procedure compared with 360° images (Baiocchi et al., 2017). Others have researched the optimal survey strategy for different types of underground constructions with changing dimensions, morphology and perforations (Porrás-Amores et al., 2019). Additionally, textured point clouds have been used to create immersive visualisations in the field of virtual reality (Clini et al., 2019), with specialised equipment allowing users to explore the interior of a space.

There are also other case studies which, despite focusing on completely different types of

heritage, make important contributions to the knowledge. In this sense, as far as the information model is concerned, the HBIM methodology has been enriched over the last ten years with many experiences that, from the professional and scientific fields, have investigated its broad perspectives of use in the management and protection of heritage architectures (Pocobelli et al., 2018). In fact, an HBIM model can encompass multiple dimensions (Castellano Román & Pinto Puerto, 2019), from incorporating a geometric and formal analytical study (3D) (Murphy et al., 2017), to containing its historical evolution (4D) (Guerrero Vega & Pizzo, 2021), conservation diagnostic work (5D) (Calvano et al., 2022), its context socio-cultural (6D) (Brumana et al., 2017) and the management of conservation and intervention activities (7D) (Bruno & Roncella, 2018). In this way, the HBIM methodology transcends the mere geometric characterization of the heritage asset and offers an effective instrument for sustainable management.

In HBIM, geometric 3D information is associated with the survey and analysis of the heritage asset. In this process, the assistance of high-precision digital capture technologies, such as photogrammetry (this case study) or 3D laser scanning, may be necessary, but it is not absolutely essential. In fact, the research group that covers this experience proclaims that the main objectives of an HBIM information model must be analysis and the generation of knowledge about the building itself, so digital capture technologies become secondary. The model must be part of an architectural survey process, in the sense defined in the Rilievo Charter: "... *the critical path of the construction process, and also the project must be verified ...*" (Jiménez Martín & Pinto Puerto, 2003).

Therefore, the technology applied in the graphic construction associated with the survey does not determine it a priori, but simply characterizes it against other methodological options. Thus, it is defended that, in general, the priority is not the achievement of high-precision three-dimensional modeling, but rather the exploration of the possibilities of HBIM as a form of knowledge of heritage construction. However, there are cases, such as the one that occupies it in this work, in which the formal complexity of the object of study forces (due to the inoperability of other techniques) the application of such technologies, in order to generate an adequate geometric base on which to support knowledge

and analysis. In any case, geometric precision is a characteristic of the HBIM model that can evolve according to its level of knowledge and development.

As an example, parametric geometry (basic characteristic of working with BIM models) (Rua & Gil, 2014), can update models automatically and, if new finds emerge, this technique is capable of completing the existing documentation without having to create the model again from scratch.

3. Research objectives

The objective pursued by the research is to evaluate the possibilities and limitations of using photogrammetric survey techniques to gather data from underground heritage elements with complex geometry, with the ultimate aim of obtaining information to generate a 3D graphic base.

This should be sufficiently detailed and capable of supporting the implementation of HBIM methodology in the knowledge and analysis process about these heritage objects.

4. Methodology

The methodology involves two stages (Fig. 1). The first one consists in gathering data and managing the existing information by reviewing and filtering the documentation found.

This not only provides a preliminary body of knowledge about the object of study but graphical documents as well on which to work and set out the scope of the research.

The second stage consists in generating new information to supplement the existing data. New data is collected to provide additional information about the heritage element.

Unlike conventional archaeological surveys, in this case a digital sample is created to conduct a photogrammetric survey and create a base 3D model to which information can be added as new data emerge, thus contributing to the digital preservation of the heritage.

The workflow therefore contains two parallel lines of action, as summarised in the diagram below:

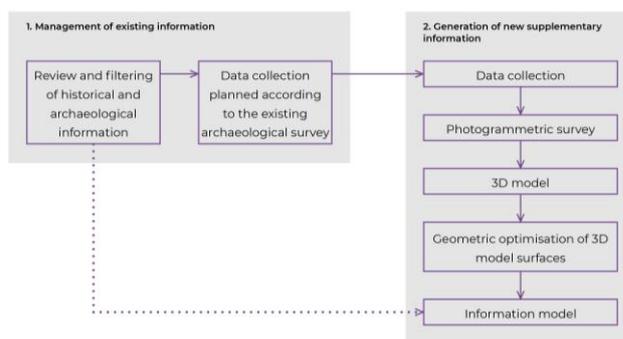


Fig. 1: Methodology diagram

5. Contextualisation of the case study

Like many other Roman towns and cities, Carmona had a complex water supply system. There were different types of systems according to the topographical characteristics of each area, but they mainly consisted of underground aqueducts, which carried water from the source to the point of demand, and cisterns, which stored rainwater from the *impluvia* in buildings (Conlin Hayes, 2001).

Carmona is situated on the edge of the “Alcores” (Fig. 2), a high ridge that adopts the form of a sloping plateau on the Guadalquivir Depression (Galera-Rodríguez et al., 2022). Different civilisations have settled in this region throughout the ages and today it is home to Carmona, El Viso del Alcor, Mairena del Alcor and Alcalá de Guadaira. The terrain in all of these towns has a similar geological composition made up of a layer calcarenite rocks (Amores Carredano, 1982). The porosity of this type of rock allows the filtration of water, forming an aquifer mantle in the subsoil when it reaches an impermeable layer.

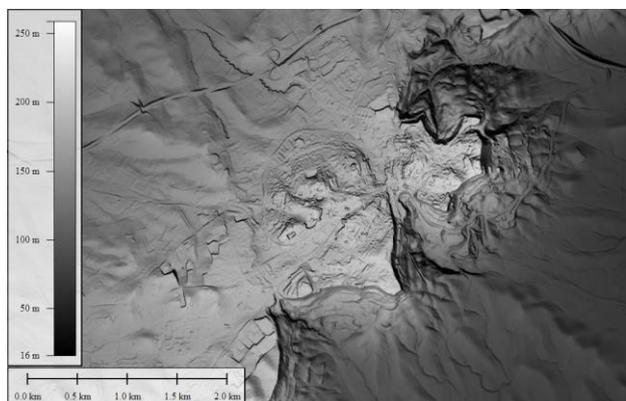


Fig. 2: Greyscale contour map of the town of Carmona. Obtained from the MDT05 database and processed in Global Mapper

The porosity of the rock greatly facilitated the excavation of the cisterns until they reached an impermeable layer, which became the bottom of the cistern.

The remainder of the cistern was clad with a layer of *opus signinum*, the impermeable mortar that was used in Roman works of engineering to avoid leaks in hydraulic infrastructures (Fig. 3).



Fig. 3: Images of the inside of the main galleries in the cistern

The cisterns are located inside the walled section of Carmona because due to the topography of the land the town is situated at a higher altitude than the surrounding landscape, making it difficult to carry water up to it from a natural source.

The capacity of each cistern depended on the type of building it serviced, which might be domestic and therefore smaller, or public, such as the baths, which required a much larger water reserve.

The hydraulic structures of the Roman town of Carmona have been the object of sporadic archaeological campaigns related to the appearance of finds, mainly identified as belonging to wells, cisterns and pipes (Orche Amaré et al., 2018).

For this case study, focused on obtaining data from a photogrammetric survey and the subsequent generation of an information model, it is chosen the cistern located at Number 6 on Calle Pozo Nuevo (Fig. 4), one of the largest of the underground structures in Carmona. This infrastructure has been preserved almost intact.



Fig. 4: Group of heritage elements in the case study, with archaeological remains of the *hypocaustum* in the baths that were serviced by the cistern, and the site of a second, smaller cistern

6. Review of existing of information

To ensure a correct understanding of the heritage object, it is important to review the bibliographies of different branches of knowledge. As a first step, a search of water supply systems in Roman cities is conducted (Fernández Casado, 1977; Moreno Gallo, 2007; Sánchez López E & Martínez Jiménez J, 2016). For this case study, different repositories are consulted but mainly the archive at the local museum in Carmona (Anglada Curado et al., 2001; Conlin Hayes, 2001) and the archaeological yearbooks for Andalusia, which review all the existing archaeological information. The survey carried out during one of the archaeological campaigns (Belén et al., 1996) provided reference plans on which to organize the collection of new data research.

7. Data collection

There are different methods for capturing data to create a high-density point cloud of the current state of the void-building. Laser scanning can be used to perform an accurate surface sweep without having to install any lighting. As an alternative method, photogrammetry requires a certain amount of light, but it is both more accessible and affordable, and therefore this technique has been chosen.

The aim was to verify and classify the information previously obtained using archaeological direct data collection methods, and the use of this technique therefore represented a major challenge in the case study due to several aspects with the potential to severely alter the

success of its implementation. The first of these aspects was the subtractive quality of the heritage object, i.e. a space excavated in the subsoil (Amores Carredano, 1982). With this survey method, data is generally collected from outside the item in question, as this offers a wider variety of viewing angles. However, this was not possible in this case because the element is underground and surrounded by soil-rock, the only point of contact with the outside being the entrance hole.

The lack of reference to the town on the surface also made it difficult to identify the exact orientation.

Secondly, the dimensions and morphology of the cistern make it difficult to take accurate photographs with minimal distortion. The sections of the structure—frustoconical shapes in all cases—never exceed 1.75 meters wide and 3.05 metres high, and in some stretches the width and height are only 1.00 and 1.5 metres, respectively. This makes it extremely difficult to collect data consistently because the geometry is irregular and the camera angle range is very limited. The structure in question is linear with different galleries, so the route followed to take the photographs is necessarily linear as well. Data collection at the ends of these drifts is particularly challenging. A third difficulty is presented by the lack of natural light. This is essential to use the photogrammetric survey method since natural light generates a constant light source with uniform intensity and color tone. In the case of the cistern, all the walls are blank except for the entrance from the basement of the house beneath which it is situated, and the top is covered by a covered well. Therefore, the penetration of natural light is impossible.

The photogrammetry method requires a set of basic equipment and other items. In this case it is used the following:

Samsung NX 3000 camera with 20 MP resolution and Samyang 14 mm f/2.8 lens.

Tripod to hold and stabilise the camera, ensuring pictures as clear as possible in poor light conditions.

Since it was impossible to use topographic equipment, a plumb bob with fixed markers is used as the reference for the scale and vertical orientation.

Artificial LED lighting, comprising different autonomous devices with independent batteries, to illuminate different points of the cistern and avoid the presence of wires that would have

distorted the results of the photogrammetric survey.

A total of 88 photographs were taken (Fig. 5). As a linear element, the only option to collect data was to perform sweeps back and forth in the various cistern galleries. The images were taken from the centre of the section at each point with the lens positioned at a height of approximately 1.50 metres with respect to the floor of the cistern. Due to the conditions of the underground space and the artificial lighting (very sparse at certain points), the photographs were taken at ISO 800 with a shutter speed of 3 seconds and a resolution of 5472 x 3684 pixels.



Fig. 5: Photographic sequence of the data collection inside the cistern to perform the photogrammetric survey

Before the data were collected, the points of light are distributed in strategic locations, mainly at the intersections of the different galleries. The plumb bob is also positioned, with 50 cm markers, at a point with maximum light.

8. Photogrammetric survey

Agisoft Metashape Professional is used for the orientation of the images and the generation of the point cloud. It is begun by setting a high-precision orientation for the various images: 50,000 key points and 10,000 tie points per photo.

Due to the geometric complexity of the element, digital photogrammetry is opted to obtain a high-density point cloud as the base for the 3D model of the cistern. The high-density point cloud was generated with medium-quality properties and aggressive filtering, therefore largely eliminating the noise from the images.

This noise was mainly caused by the medium/low level of light in the cistern and the use of artificial light. The filtering eliminated erroneous points with an incorrect depth and simplified the subsequent point cloud cleaning process.

As photographs were taken inside the surveyed object, all the identified points corresponded to the element itself and there was no need to manually filter the points corresponding to context elements.

Two markers are placed at different heights in the 11 photographs in which the plumb bob appeared. These corresponded to metric points marked on the plumb bob, which allowed it to scale the point cloud and obtain the true vertical orientation of the cistern.

Having generated the point cloud is exported in .txt format and then imported it to CloudCompare v2.11.3 for optimisation. The point cloud generated in Agisoft Metashape comprises 24,748,873 points. In this case study the aim was to obtain a point cloud as uniform as possible to be able to define the entire heritage element on a global scale. It is not intended to model a specific fragment with an extremely high level of detail and a detailed scale. To ensure more fluid control of the cloud in CAD, the distance between points is reduced to 2.5 centimetres, finally obtaining 1,775,050 points. This type of filtering does not excessively alter the morphology of the point cloud and is of sufficient quality to be able to model the element without a significant variation in the margin of error precision of the point cloud.

Having reduced the number of points, we proceeded to clean the cloud. During this process the points with an excessive margin of error were identified. Although eliminated the noise was previously eliminated in the image orientation process, due to the light conditions and dimensions of the cistern, the software generated

depth maps with errors in certain areas, producing isolated points that had a different depth from that of the cistern contours.

After optimising the point cloud and cleaning up the bad points, a set of points is obtained that defines the cistern volumes with a reasonable level of accuracy (Fig. 6). This allowed it to generate a uniform mesh without discontinuities produced by poorly positioned points. To facilitate interoperability between different software programs, the mesh file is exported in .stl format for sharing 3D mesh model information.

9. 3D modelling

Creating a 3D model of the cistern on the basis of the photogrammetric survey presented one of the greatest challenges. The goal was to model a unique complex geometry with a standard system based on stacking typical components for management on a BIM platform.

The heritage elements where BIM models are used are usually unitary constructions with a relatively simple morphological composition, so it is possible to model directly in BIM software using an imported point cloud as a reference.

There are several reasons why this was not an option in the case of this cistern. In the first place, it does not contain generic elements or a regular or orthogonal geometry, but rather organic surfaces generated by the excavation and the unevenness of the rock on the Alcores hill. Secondly, it is not even a building with defined and identifiable construction features, but an irregular space dug out in the ground without an envelope or directrix



Fig. 6: Clean high-density point cloud generated with CloudCompare

for the components. All of this makes it technically impossible to create an accurate model of this geometry directly in BIM software, in this case Autodesk Revit®. Modeling exclusively in this program would only generate approximate volumetric information, defined by contours serving as the directrix for the envelope, but the wall components and levels would be entirely flat surfaces that could not precisely fit the oval shape of the cistern. This would allow it to obtain an approximate model with a low level of detail that could just as easily be generated with the pre-existing survey, thus eliminating the need for photogrammetric data capture.

To create an accurate model of the cistern an alternative to the direct method is sought, enabling to model the geometry of this heritage element with precision and accuracy. To do this, different computer-aided drawing programs are used which, after an arduous process managed to import the geometries to BIM software.

The mesh previously generated and optimised in CloudCompare was imported to Rhinoceros 6® as a .stl file. Then it is scaled and obtained the vertical orientation, for which the markers used in the generation of the point cloud in Agisoft Metashape are imported in .dxf format. Once the coordinates of the points are obtained, we performed the scaling and alignment and managed to obtain the real vertical orientation of the cistern. Since it was only able to collect metric data for the z axis and had no geo-referenced points, common points are used on the existing plans to align the x and y axes.

To generate the surface, a directrix curve is drawn along the axis of the cross sections of the different galleries in the cistern (Fig. 7). In the curves of the galleries fillet radii are created to obtain the various transition curves.



Fig. 7: Directrix along the axis of the cistern section. Rhinoceros 6®

Using curve matrices perpendiculars to the directrix at 10 centimetres intervals are created on

the curve of the directrix. This interval is considered optimal for achieving a balance between obtaining a surface that is not excessively complex and therefore can be manipulated, and obtaining a sufficient level of detail to be able to accurately describe the heritage object. These parameters work efficiently on stretches with a minimal curvature because the intervals between the planes on the interior and exterior edges of the cistern are similar, but they are far less efficient at the intersections of the different galleries. With the initial fillet radii, the interval on the lower edge planes of the curvature was barely 2 millimetres and more than 25 centimetres on the exterior edge (Fig. 8a). The lower edge interval would cause problems in the generation of the surface due to the excessive proximity of the section curves. The gap on the exterior edge planes was much larger than the interval on all the other stretches, which means that information about the element modeled would be lost, especially on a surface that curves in both directions. These intervals were therefore intolerable because they would have produced perforations and discontinuities when generating the surface, which in any case would be too heterogeneous because the variation in the distance between the different control points would be excessive.

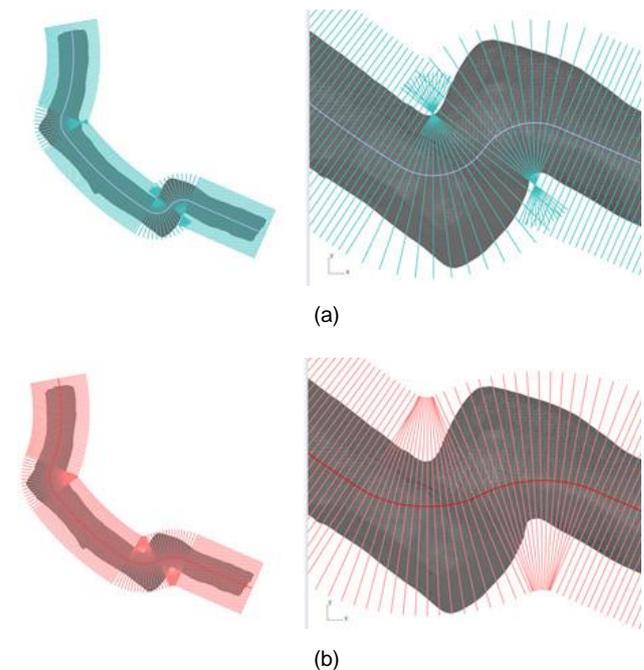


Fig. 8: Perpendicular planes to the directrix plane along the cistern axis. (a) Errors and initial hypothesis. (b) Directrix smoothed at the twists and turns and modification of sections

To reduce these errors, the fillet curves of the directrices of the different galleries are smoothed by moving their points of control. This created a minimal distance of 3 centimetres on the lower edge of the curve and 17 centimetres on the exterior edge (Fig. 8b). These intervals, which bear a greater similarity to the other stretches of the gallery, generated greater uniformity in the data of the model to generate also in addition to optimising the surfaces.

Another problem arose at both ends of the gallery due of the absence of sections perpendicular to the walls. To be able to model these parts without creating more errors of information with respect to other areas, the interval between the planes at both ends was reduced from 10 to 5 centimetres.

With the generated plans, intersections are created in the cistern mesh obtained from the photogrammetric survey with these planes. This produced 207 different cistern sections which describe the element in 3D based on closed curves (Fig. 9).



Fig. 9: Cross sections of the cistern. Rhinoceros 6 ®.

Before creating the surface, the elements of the sections are removed with inaccuracies for modelling at a later time, i.e. the wells and gallery entrances. This generated a more uniform surface and smoothed the control point transitions. To do this, the intersection curve is traced by curve at the fillet points with the cistern, closing the gap with curves to maintain the standard section.

The zones where a lack of precision is detected on the surface with respect to the section obtained due to inaccuracies in the cloud, such as excessive twists in the curves or deviations from the middle section of the stretch, it is rectified this by moving the points of these curves, finally obtaining more accurate sections.

Having corrected the curves, a transition surface is generated (Fig. 10). After running partial tests, it is decided to create the surface of the entire volume rather than dividing it into separate parts at this point because it would have been difficult to assemble them and maintain continuity between all the control points. The surface was generated with 80 control points in each section, creating a 10 x 10 centimetre grid of control points. This interval is considered an optimal distance because it preserves the properties of the sections while making it possible to modify the control points as necessary, avoiding an overly dense mesh of points that would be difficult to manipulate for the desired level of detail. It is also opted for a tight style, so the surface generated adapts to the section curves as closely as possible.

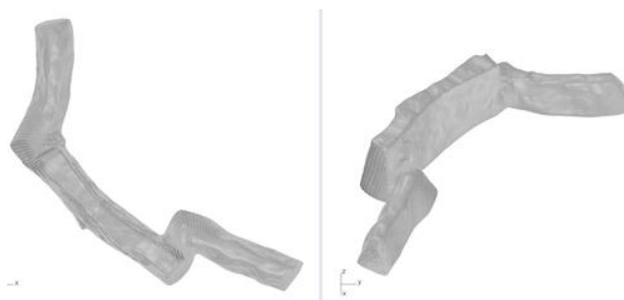


Fig. 10: Transition surface based on the cross sections. Rhinoceros 6 ®.

Photogrammetry enabled it to generate a 3D model of the main cistern galleries but there are elements on a smaller scale which, due to their dimensions, difficulty of access or lack of light have not been accurately captured. These elements are modelled with graphical and descriptive

information (Fig 11). To do this, floor plans and sections from the archaeological campaign are inserted as references to model the well and the gallery that emerges in the central point of nave. Elements such as perforations in the ceiling or the current access to the cistern were captured in the photogrammetric point cloud but only partially. To create the model, it was necessary to interpret the information at one of the intersections and compare it with the existing images.

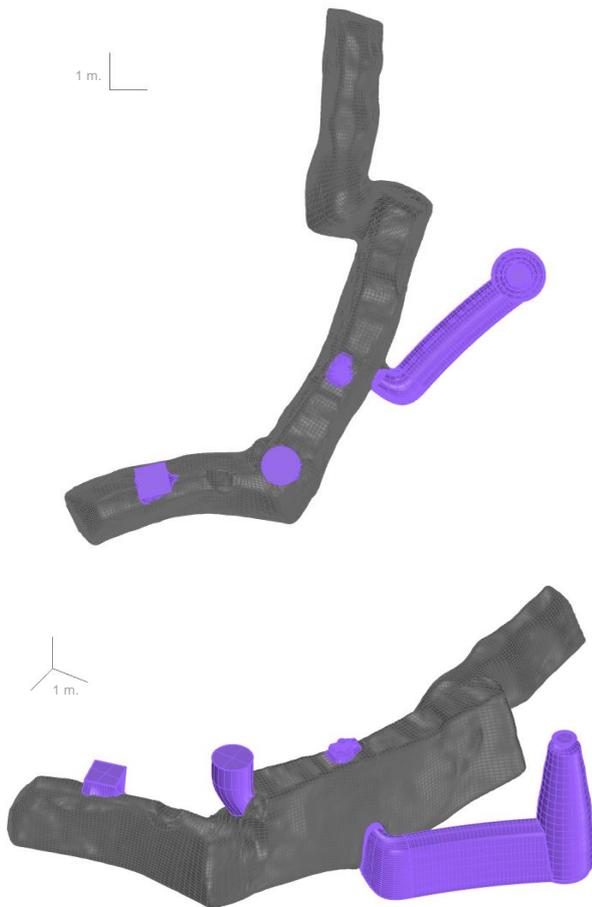


Fig. 61: Complete 3D model, including pieces modelled from the photogrammetric model and pieces modelled from the archaeological survey. Rhinoceros 6®

Having generated all the interior volumes of the cistern A test is run to import all the surfaces in Autodesk Revit®. This confirmed that many of the surfaces generated could not be imported with any of the possible file extensions. It was only able to insert pieces that had been modelled in a simplified manner from the archaeological cartography. These have less complex geometries because they have been modelled from simple curves rather than from complex curves related to the cloud point mesh.

Autodesk Revit® crashes when importing surfaces that are not completely closed or that have excessive twists and turns, and for the problematic pieces it is therefore opted to use an alternative transformation process based on reverse engineering software. This makes it possible to optimise the process and resolve the incidents generated, simultaneously achieving interoperability between the different software programs and models.

The optimisation process and simplification of the surfaces is initiated using reverse engineering programs. The first step was to insert the Rhinoceros® surfaces in MeshLab. These surfaces have to be closed for the program to read them properly. A closed mesh is created from the surface. For this operation, it is necessary to find a balance in the mesh accuracy by grading the resolution of each point in the form as optimally as possible. This meant that, each piece had to be regulated to the level of precision best suited to the form (Fig. 12). Having obtained the mesh it is saved it as an .obj file.

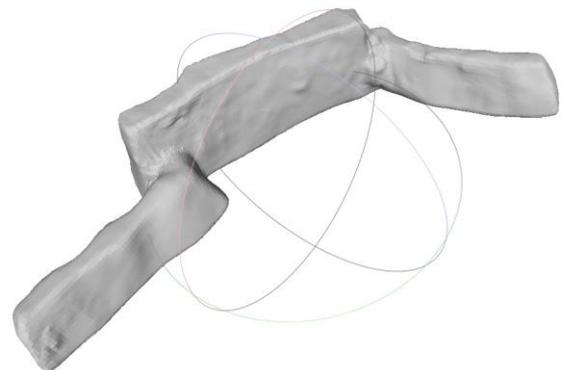


Fig. 12: Mesh generated from Rhinoceros 6 surface. MeshLab

The closed mesh was then inserted into the reverse engineering software, Geomagic Design X to complete the optimisation process. This program enabled it to transform the previously generated mesh into a closed surface (Fig 13). To do this, it is defined the precise number of patches to generate that would enable it to import it correctly to Autodesk Revit®. In cases where the geometry was more complex, the mesh had to be smoothed or improved first to create an optimal surface for export. The closed surface is exported in .stp sharing format.



Fig. 13: Closed surface generated from the mesh in MeshLab. Geomagic Design X

The surface was now optimised but due to interconnection incompatibilities between different software programs (Tab. 1), specifically Geomagic Design X and Autodesk Revit®, it is necessary to perform an intermediate export step. The surface is inserted into Autodesk Autocad® to be able to save it with the extension .dwg and then import it to Autodesk Revit®.

Tab. 1: Methodology for the optimisation process and interoperability between 3D models with complex geometry and BIM software, using reverse engineering software.

Software	Geometric type	File format
1. Rhinoceros 6®	Surface	.obj
2. MeshLab	Closed mesh	.obj
3. Geomagic Design X	Surface	.stp
4. Autodesk Autocad®	Surface	.dwg
5. Autodesk Revit®		

Having proposed the methodology for importing the elements with complex geometry to BIM software using reverse engineering programs, the attention is turned to the thickness of the cistern layers. As it is an underground element, only its interior face is known with certainty. To define the thickness of the cladding layers of the different pieces, the data collected during the archaeological prospection is compared with the data obtained from visual inspections of the areas where the *opus signinum* coating has been lost or at the intersections between pieces.

Having obtained the thickness of each layer, to create a model of the solid elements it is necessary first to generate an interior and exterior surface for each layer and piece. This process is repeated as many times as was necessary to create solid

layers, which made the 3D modelling process considerably slower.

10. Digital information model

The aim of investing so much effort into achieving interoperability between 3D models with complex geometry and BIM software is to create an accurate model capable of containing all the existing information in a systematic and standardised manner. For this, the model needs to contain alphanumeric information classified in fields related to the description, documentation and conservation of the heritage element. This provides easy access to the data for the different agents involved in heritage management and helps to create active documentation that can be edited and supplemented at any time. It is important to define the desired level of development. When working with models related to heritage objects, it is better to define a level of knowledge (LOK) (Castellano Román & Pinto Puerto, 2019) based on the degree of information obtained from the heritage element, rather than a standard level of development (LOD) for BIM models. In this case, a LOK 100 model was created containing basic identification, location and orientation data about the overall element to enable extrapolation to the other cisterns in the network of underground structures, and a LOK 200 model with all the information obtained from the new survey. This identifies the basic structures and stages of construction while also establishing a hierarchy of the different components and layers that make up the cistern. An exploded view of the components is generated according to their morphological composition (Fig. 14), differentiating between the main gallery, where the photogrammetric capture is conducted, and all the secondary elements, such as the secondary gallery, well and perforations. Other exploded views based on material composition or historical evolution were ruled out due to insufficient scientific proof to verify their accuracy. Having obtained a disaggregated model, a set of information fields are established to describe the cistern's features. Although these parameters are specific to this concrete type of heritage asset, reflecting its unique quality, they can be applied to future research of similar heritage elements (Tab. 2). As such, it should be possible in the future to generate a joint database and a unified information model for all the underground structures in Carmona.

Tab. 2: Table caption

Parameters
Component code
Spatial element/category
Date
Description
Building component
Material
Finish
Thickness
State of conservation
Pathologies

11. Discussion

Digital photogrammetric capture not only proved to be a useful tool for obtaining detailed information about a heritage object with irregular geometry in all three dimensions, namely the cistern in Carmona, but will mean that future researchers studying other aspects of the object will be able to extract new data about it.

Meanwhile, the point cloud facilitates practically an infinite number of points of view of the interior, making it possible to plan promotional strategies based on visualisations in

augmented and virtual reality in future research projects. Underground elements are difficult to access but these tools will enable users to explore them virtually.

The workflow used to optimise surfaces with complex geometry achieved the aim of transforming and simplifying the geometry, enabling it to associate it with BIM software. This method can also be applied to other types of underground elements.

However, the programs used (Rhinoceros 6® - MeshLab - Geomagic Design X - Autodesk Autocad® - Autodesk Revit®) require specific technical skills and computer equipment, which in certain cases may hinder both the processing and management of the information by the different agents involved in heritage management and protection.

This research focuses on data collection and, even more importantly, on the optimisation of surfaces with complex geometry to be able to import them to BIM software without having to conceive an information model as such.

It therefore establishes a base on which to create a complete BIM model when a greater volume of information about the object is obtained, which will enable it to define it in more detail and within the context of the current city on the surface above it.

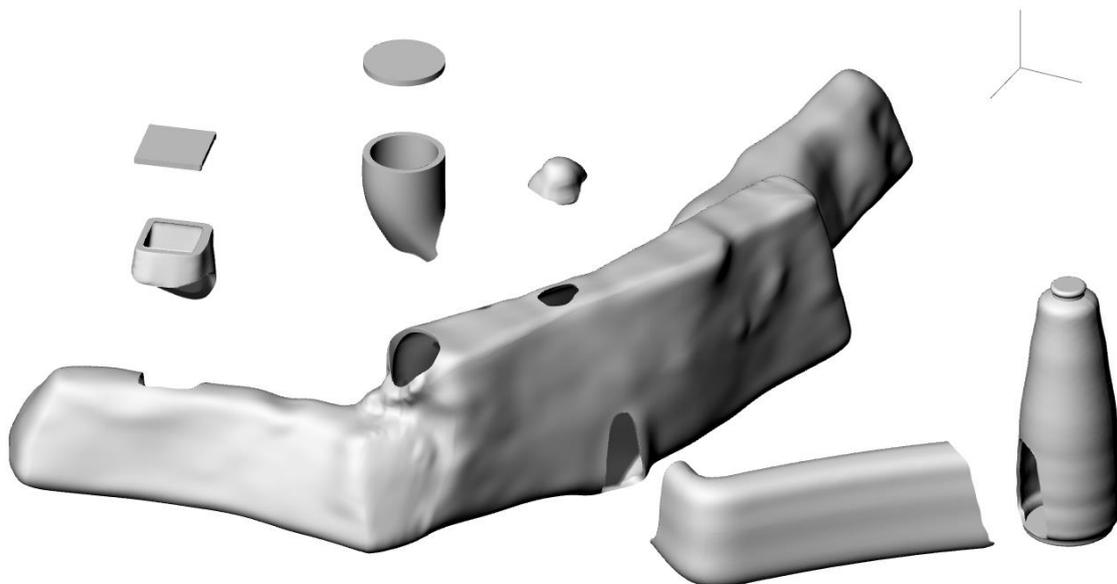


Fig. 14: Exploded view of the LOK 200 HBIM model showing the different components

Conclusions

The complex morphology of this heritage object and its underground location created a series of technical difficulties that had to be overcome during the documentation process.

The methodology used proved capable of collecting verifiable data with the necessary level of detail to ensure the efficient management of the heritage asset.

The choice of photogrammetry rather than laser scanning to capture the data facilitated to manipulate and disaggregate the graphical information obtained, resulting in both time and cost savings regarding the capture and computer equipment.

The photogrammetric capture was conditioned by the type of heritage and its underground location, which created limitations due to the lack of natural light, the small size of the space and the inability to capture the exterior face and identify the thickness of the layers.

The generation of digital models of heritage spaces significantly improves their documentation and management.

In this particular case, it was not enough to create an information model directly from the point cloud; a specific procedure must be adapted to the factors that characterise this heritage typology.

The working method followed enabled it to create a 3D model of surfaces with complex geometry from a 3D point cloud and to test a protocol for optimising and associating these surfaces with BIM software.

The use of reverse engineering programs was a key factor in the transformation of the surfaces, enabling it to simplify the geometry of the object without losing relevant information.

Meanwhile, the accuracy obtained in the model allowed it to formulate an analytical proposal about its morphological composition and construction, consisting in turning the different components into discrete elements to facilitate the creation of a detailed classification system.

The work procedure employed can be applied to future research of similar heritage spaces, therefore favouring the unification of heritage documentation criteria.

Generating unified information that can be updated and, above all, can be accessed by the agents involved is key to promoting a genuine public appreciation of heritage.

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REFERENCES

- Alessandri, L., Baiocchi, V., Del Pizzo, S., Di Ciaccio, F., Onori, M., Rolfo, M. F., & Troisi, S. (2020). A flexible and swift approach for 3D image-based survey in a cave. *Applied Geomatics*. <https://doi.org/10.1007/s12518-020-00309-4>
- Amores Carredano, F. (1982). *Carta arqueológica de los Alcores (Sevilla)*. Diputación Provincial de Sevilla.
- Angelini, M. G., Baiocchi, V., Costantino, D., & Garzia, F. (2017). Scan to BIM for 3D reconstruction of the papal basilica of saint Francis in Assisi In Italy. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(5W1), 47–54. <https://doi.org/10.5194/isprs-Archives-XLII-5-W1-47-2017>
- Anglada Curado, R., Belén Deamos, M., Conlin Hayes, E., & Jiménez Hernández, A. (2001). El uso del agua en Carmona. Las termas de la calle Pozo Nuevo. In *Carmona Romana* (pp. 209–232).
- Baiocchi, V., Barbarella, M., Del Pizzo, S., Giannone, F., Troisi, S., Piccaro, C., & Marcantonio, D. (2017). Augusto's sundial: Image-based modeling for reverse engineering purposes. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2W3), 63–69. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-63-2017>
- Belén, M., Anglada, R., Conlin, E., & Jiménez, A. (1996). Excavaciones en Carmona (Sevilla) Las termas de la calle Pozo Nuevo. In *Anuario arqueológico de Andalucía 1996* (Junta de Andalucía, pp. 630–639).
- Benavides López, J. A., Martín Civantos, J. M., & Rouco Collazo, J. (2020). Levantamiento arquitectónico y análisis arqueológico del castillo de Píñar como punto de partida para su conservación. *Virtual Archaeology Review*, 11(22), 95. <https://doi.org/10.4995/var.2020.12397>
- Brumana, R., Dellatorre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., Franchi, A., Banfi, F., Della Torre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., Franchi, A., & Banfi, F. (2017). HBIM challenge among the paradigm of complexity, tools and preservation: The basilica Di collemaggio 8 years after the earthquake (L'aquila). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, XLII(September), 97–104. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-97-2017>
- Bruno, N., & Roncella, R. (2018). A restoration oriented HBIM system for cultural heritage documentation: The case study of parma cathedral. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. <https://doi.org/10.5194/isprs-archives-XLII-2-171-2018>
- Burens, A., Grussenmeyer, P., Carozza, L., Lévêque, F., Guillemin, S., & Mathé, V. (2014). Benefits of an Accurate 3D Documentation in Understanding the Status of the Bronze Age Heritage Cave “Les Fraux” (France). *International Journal of Heritage in the Digital Era*, 3(1). <https://doi.org/10.1260/2047-4970.3.1.179>
- Calvano, M., Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Parametric Processes for the Implementation of HBIM — Visual Programming Language for the Digitisation of the Index of Masonry Quality. *International Journal of Geo-Information*, 11(93). <https://doi.org/https://doi.org/10.3390/ijgi11020093>
- Castellano Román, M., & Pinto Puerto, F. (2019). Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain). *Digital Applications in Archaeology and Cultural Heritage*, 14, e00110. <https://doi.org/10.1016/J.DAACH.2019.E00110>
- Chikatsu, H., & Takahashi, Y. (2009). Comparative evaluation of consumer grade cameras and mobile phone cameras for close range photogrammetry. In F. Remondino, M. R. Shortis, & S. F. El-Hakim (Eds.), *Videometrics, Range Imaging, and Applications X* (Vol. 7447, p. 74470H). SPIE. <https://doi.org/10.1117/12.825746>
- Clini, P., Nespeca, R., Angeloni, R., & Mammoli, R. (2019). THE INTEGRATED SURVEY of NARROW SPACES and UNDERGROUND ARCHITECTURE: The CASE STUDY of CAMPANA CAVES BAS-RELIEFS. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W9). <https://doi.org/10.5194/isprs-archives-XLII-2-W9-277-2019>
- Conlin Hayes, E. (2001). El abastecimiento agua en la Carmona romana. In *Carmona Romana* (pp. 203–217).

Fernández Casado, C. (1977). Los depósitos de agua de las conducciones romanas. *Revista de Obras Públicas*, 3145, 379–398.

Galera-Rodríguez, A., Pinto-Puerto, F., & Algarín-Comino, M. (2022). *From Historical Representation to Spatial Data Infrastructure. Contextualisation of the Underground Heritage Spaces in the City of Carmona (Seville)*. 77–85. https://doi.org/10.1007/978-3-031-04632-2_9/COVER/

Galli, M., Griffo, M., Inglese, C., & Ismaelli, T. (2019). Vecchi scavi e nuove tecnologie: Primi risultati del progetto basilica iulia. *Archeologia e Calcolatori*, 30, 229–249.

García-Molina, D. F., González-Merino, R., Rodero-Pérez, J., & Carrasco-Hurtado, B. (2021). Documentación 3D para la conservación del patrimonio histórico: el castillo de Priego de Córdoba. *Virtual Archaeology Review*, 12(24), 115. <https://doi.org/10.4995/var.2021.13671>

Guerrero Vega, J. M., & Pizzo, A. (2021). Análisis arquitectónico y aplicación de metodología BIM en el santuario extraurbano de Tusculum. *Archeologia e Calcolatori*, 2(32.1), 99–116. <https://doi.org/10.19282/ac.32.1.2021.06>

Jiménez Martín, A., & Pinto Puerto, F. (2003). *Levantamiento y análisis de edificios: tradición y futuro*. Universidad de Sevilla, Secretariado de Publicaciones.

Moreno Gallo, I. (2007). El arte romano del abastecimiento de aguas. *Cimbra: Revista Del Colegio de Ingenieros Técnicos de Obras Públicas*, 374, 14–33.

Murphy, M., Corns, A., Cahill, J., Eliashvili, K., Chenau, A., Pybus, C., Shaw, R., Devlin, G., Deevy, A., & Truong-Hong, L. (2017). Developing historic building information modelling guidelines and procedures for architectural heritage in Ireland. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-539-2017>

Murphy, M., MCGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, 27(4), 311–327. <https://doi.org/10.1108/02630800910985108>

Nocerino, E., Menna, F., & Remondino, F. (2014). Accuracy of typical photogrammetric networks in cultural heritage 3D modeling projects. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 40(5), 465–472. <https://doi.org/10.5194/isprsarchives-XL-5-465-2014>

Orche Amará, P., Millán Naranjo, J., & Román Rodríguez, J. M. (2018). Las minas de agua de los alcores sevillanos: unas monumentales obras hidráulicas subterráneas de época romana que empiezan a salir a la luz. In Junta de Andalucía & Fundación Patrimonio Industrial de Andalucía (Eds.), *II Congreso Internacional de Patrimonio Industrial y de la Obra Pública Patrimonio Industrial: pasado, presente y futuro* (pp. 378–394). Francisco Javier Sánchez Jiménez (coord.).

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018). BIM for heritage science: a review. *Heritage Science*, 6, 30. <https://doi.org/10.1186/s40494-018-0191-4>

Porras-Amores, C., Mazarrón, F. R., Cañas, I., & Villoria Sáez, P. (2019). Terrestrial laser scanning digitalization in underground constructions. *Journal of Cultural Heritage*, 38. <https://doi.org/10.1016/j.culher.2019.01.007>

Rodríguez González, P., Nocerino, E., Menna, F., Minto, S., & Remondino, F. (2015). 3D Surveying and modeling of underground passages in WWI fortifications. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 40(5W4). <https://doi.org/10.5194/isprsarchives-XL-5-W4-17-2015>

Rua, H., & Gil, A. (2014). Automation in heritage-Parametric and associative design strategies to model inaccessible monuments: The case-study of eighteenth-century Lisbon Águas Livres Aqueduct. *Digital Applications in Archaeology and Cultural Heritage*, 1(3–4), 82–91. <https://doi.org/10.1016/j.daach.2014.06.002>

Sánchez López E, & Martínez Jiménez J. (2016). (PDF) *Los acueductos en Hispania: construcción y abandono*. <https://doi.org/https://doi.org/10.17863/CAM.8797>

Valls, A., García, F., Ramírez, M., & Benlloch, J. (2015). Understanding subterranean grain storage heritage in the Mediterranean region: The Valencian silos (Spain). *Tunnelling and Underground Space Technology*. <https://doi.org/10.1016/j.tust.2015.07.003>

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. In *Automation in Construction* (Vol. 38). <https://doi.org/10.1016/j.autcon.2013.10.023>