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INFORMATION PROCESSES IN VIRTUAL 3D RECONSTRUCTION OF ROMAN THREE-BAY DOUBLE ARCH OF MUSTI (TUNISIA)

PROCESOS DE INFORMACIÓN EN LA RECONSTRUCCIÓN VIRTUAL EN 3D DEL DOBLE ARCO ROMANO DE TRES TRAMOS DE MUSTI (TÚNEZ)

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Highlights:

- The article highlights the integration of advanced modelling software, showcasing their potential in reconstructing historical monuments with high accuracy and detail.
- The study uses modern techniques such as LiDAR, photogrammetry, and HBIM compared with historical documentation in digital 3D reconstruction.
- Reality-based parametric modelling and virtual anastylosis were employed to verify and visualise hypotheses about the original structure of the arch.

Abstract:

The case study focuses on the virtual hypothetical 3D reconstruction of the Roman Three-bay Double Arch of Musti, Tunisia. This work, part of the AFRIPAL project, aims to enhance understanding of the Romanisation and urban development of Musti between the 5th century BC and the 3rd century AD. It builds on research by Professor Naïdè Ferchiou, who provided a detailed reconstruction hypothesis based on measurements and documentation from the 1990s. Modern techniques such as Light Detection and Ranging (LiDAR) scanning, photogrammetry, Building Information Modelling (BIM), and algorithmic modelling were employed to visualise and verify this reconstruction. Scans of existing architectural fragments were used to create high and low-polygon models, enabling the testing of various hypotheses. The study highlights the use of tools like Reality Capture, Archicad, Rhino, and Grasshopper to reconstruct historical monuments, focusing on accuracy in modelling and detailed parametric representations. One of the main challenges was reconstructing the arch despite significant alterations due to centuries of redevelopment and later modifications. That challenge was addressed by cross-referencing historical documentation with modern scanning technologies and photogrammetry. Textured mesh and boundary representation (BREP) modelling were incorporated with virtual anastylosis of elements to hypothesise the original structure. The study concludes by showcasing photorealistic visualisations of the reconstructed arch and discussing the potential for automating aspects of the reconstruction process using modern software. This work brings to life an ancient Roman monument and sets a workflow for future detailed virtual reconstructions of cultural architectural heritage.

Keywords: parametric modelling; Heritage Building Information Modelling (HBIM); virtual anastylosis, Light Detection and Ranging (LiDAR); photogrammetry; 3D reconstruction

Resumen:

El estudio de caso se centra en la reconstrucción virtual hipotética en 3D del doble arco romano de tres tramos de Musti, Túnez. Este trabajo, que forma parte del proyecto AFRIPAL, tiene como objetivo mejorar la comprensión de la romanización y el desarrollo urbano de Musti entre el siglo V a.C. y el siglo III d.C. Se basa en la investigación del profesor Naïdè Ferchiou, quien proporcionó una hipótesis de reconstrucción detallada basada en mediciones y documentación de la década de los 1990. Para visualizar y verificar esta reconstrucción se emplearon técnicas modernas como el escaneo LiDAR, la fotogrametría, el '*Building Information Modelling*' (BIM) y el modelado algorítmico. Se utilizaron escaneos de fragmentos arquitectónicos existentes para crear modelos poligonales de alta y baja resolución, lo que permitió probar varias hipótesis. El estudio destaca el uso de herramientas como Reality Capture, Archicad, Rhino y Grasshopper para reconstruir monumentos históricos, centrándose en la exactitud del modelado y la representación paramétrica detallada. Uno de los principales desafíos fue reconstruir el arco a pesar de las importantes alteraciones debidas a siglos de remodelación y modificaciones posteriores. Ese desafío se abordó mediante referencias cruzadas de la documentación histórica con las tecnologías modernas de escaneado y fotogrametría. Se incorporaron modelos texturizados y modelado de representación de límites (BREP) con anastilosis virtual de los elementos que permitían hipotetizar la estructura original. El estudio concluye mostrando visualizaciones fotorrealistas del arco reconstruido y discutiendo el potencial en la automatización de aspectos

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del proceso de reconstrucción utilizando software moderno. Este trabajo da vida a un antiguo monumento romano y establece un flujo de trabajo para futuras reconstrucciones virtuales detalladas del patrimonio arquitectónico cultural.

Palabras clave: modelado paramétrico; HBIM; anastilosis virtual; LiDAR; fotogrametría; reconstrucción 3D

1. Introduction

The case study presented here is based on archaeological work that was conducted under the project "(Reading) African Palimpsest: The dynamics of urban and rural communities of Numidian and Roman Mustis (AFRIPAL)," a grant from the National Science Centre (NCN), number 2020/37/B/HS3/00348.

It is part of the CoVHer Erasmus+ project (Computer-based Visualisation of Architectural Cultural Heritage, 2021-1-IT02-KA220-HED-000031190), coordinated by the University of Bologna between 2022 and 2025 (CoVHer, 2023). CoVHer's one of the primary goals is to establish shared standards for creating and validating virtual reconstructions of the past, with a specific focus on positioning 3D models as scientific products. Given the project's multidisciplinary nature, it involves archaeologists, architects, engineers, art historians, and restorers. From an operational standpoint, the project seeks to build upon and extend the principles and best practices outlined in key frameworks such as the London Charter (Denard, 2012), the Seville Principles (ICOMOS, 2017), and the FAIR Principles (Wilkinson et al., 2016).

This work continues and advances the research carried out by Prof. Naïdè Ferchiou, a Tunisian archaeologist whose work has focused on Roman North Africa. The main objective of this work was to analyse the hypothetical reconstruction described in detail and drawn by Prof. Ferchiou to verify and visualise it using modern techniques. The secondary objective was to create an algorithmic process to test different possible variants.

1.1. Information process in architectural heritage course

The presented case study was used as didactic source material in the course "Information Processes in Architectural Heritage" on a Master's degree program - Architecture for Society of Knowledge (Faculty of Architecture, Warsaw University of Technology), to test and extend the CoVHer approach in practice.

The course introduces architecture students to using modern algorithmic tools with historical objects based on archaeological research. It is designed as a hands-on workshop, where students engage in collaborative design activities that involve constant group participation in reviewing work progress, discussions, and critical assessments of each project phase. The primary focus is on creating a model of an object that serves both as a tool for design and a repository of information about its cultural significance. Throughout the course, students develop primary reconstructions compared with proposed additions and adaptations. The digital model's simulation capabilities are used to assess the value of these interventions and ensure the preservation or enhancement of the object's cultural heritage.

IPAH covers essential concepts related to architectural and cultural heritage, critical analysis of sources, and the creation of digital 3D reconstructions, following principles from Heritage Building Information Modelling (HBIM) (Arayici et al., 2017) and the Scientific Reference Model (SRM) framework (Kuroczyński et al., 2023).

A vital component of the course is using digital tools to analyse various historical sources and datasets related to the ancient Roman city of Musti in Tunisia. The outcome of the course is a design project that showcases a virtual 3D reconstruction based on the studied architecture, using modern communication, documentation, and visualisation techniques.

The course involves three collaborative groups, each focusing on a different aspect of a parametric digital reconstruction (Fig. 1). The Modelling group gathered information, built a database, and developed an HBIM parametric model of the existing elements. They were working in Archicad 27 on a shared file. The simulation group focused on creating a process that allows for the generation of alternative virtual reconstructions by manipulating parameters with a graphical description of this process. The visualisation group was responsible for the visualisation of the reconstructions, emphasising the hypothetical and parametric nature of the model. They explore various methods, including Augmented Reality (AR), Virtual Reality (VR), 3D printing, 360 renderings, and user interaction.

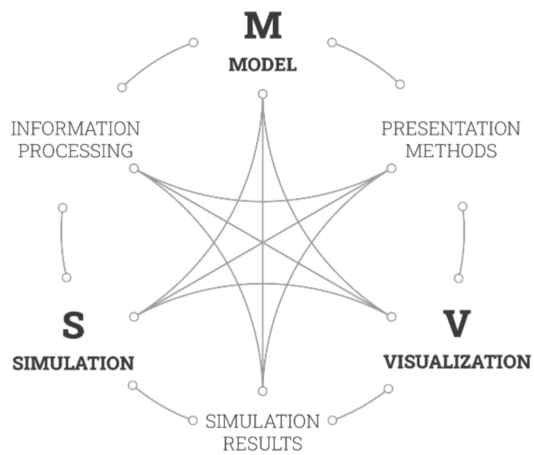


Figure 1: Scheme representing groups' collaboration.

1.2. Accurate modelling of historic structures

One of the foremost challenges is the architectural complexity inherent in historic buildings. Unlike modern structures, historic edifices often feature irregular configurations, intricate details, and unique architectural elements that defy standardisation (Fai et al., 2011). These complexities make it challenging to create accurate models using traditional BIM programs, typically designed for modern construction with standardised components.

Limited access to certain parts or information about historic structures further complicates the modelling process. Areas such as basements, attics, or ornate façade details may be inaccessible without specialised equipment or may have deteriorated to the point of being unsafe (Baik et al., 2014). This restricted access hampers the ability to collect accurate measurements and data, leading to model gaps and compromising their overall fidelity. The scarcity of accurate historical data is another significant obstacle. Over centuries, historic buildings may have undergone numerous transformations due to renovations, additions, or natural decay, often without comprehensive documentation (Dore & Murphy, 2012). This lack of precise historical records necessitates reliance on advanced technologies and expert interpretation to accurately reconstruct original designs and materials.

To address these challenges, HBIM has emerged as a specialised approach tailored for heritage buildings. It extends the principles of BIM by integrating historical data, including original construction details, material changes over time, and traditional building techniques, into comprehensive 3D models (Murphy et al., 2009). This method facilitates the preservation and conservation of historic buildings by providing detailed digital representations that account for their historical and architectural characteristics.

Advanced data collection technologies like laser scanning and photogrammetry are instrumental in HBIM. Laser scanning involves projecting laser beams onto the surfaces of structures and measuring the reflected signals to create high-density point clouds that represent the building’s geometry with exceptional accuracy (Lerma et al., 2010). This technology is beneficial for capturing intricate details and geometries that are difficult to measure manually. Photogrammetry complements laser scanning by using high-resolution photographs to generate 3D models. Photogrammetry software reconstructs the three-dimensional form of structures by analysing multiple overlapping images from different angles (Gruen, 2012). This method is advantageous for its cost-effectiveness and ability to capture colour and texture information, enhancing the visual realism of the models.

Despite the advancements, challenges persist in the implementation of HBIM. Organisational and technical issues, such as the high cost of equipment and software, the need for specialised training, and compatibility problems between different software platforms, can hinder widespread adoption (Dore & Murphy, 2012). Moreover, integrating interdisciplinary data requires effective communication and collaboration among architects, engineers, historians, and conservationists.

1.3. Adding information

The creation of the 3D model not only represents geometric aspects but also integrates material properties, textures, and other relevant characteristics. Semantic enrichment is applied by embedding metadata about materials, historical significance, and structural conditions, bridging the gap between raw data and HBIM (Argasiński & Kuroczyński, 2023).

The enriched 3D models are integrated into HBIM databases, linking them to various types of documentation and metadata accessible to architects, conservators, historians, and engineers. Advanced technologies like cloud computing facilitate collaborative access and management of large datasets through platforms like Autodesk BIM 360. Artificial intelligence enhances integration by automating feature recognition and maintenance prediction tasks. At the same time, VR and AR technologies provide immersive experiences for exploring 3D representations, aiding in virtual tours, training, and education (Yang et al., 2020).

Despite challenges like high costs and the need for specialised expertise, integrating 3D modelling with HBIM offers substantial benefits. It improves accuracy in heritage documentation, enhances conservation planning, and fosters better stakeholder collaboration. This integration provides a pathway to more effective and sustainable heritage management, leveraging technological advancements to preserve architectural heritage for the future (Historic England, 2017).

1.4. Algorithms for heritage

Developing custom scripts and algorithms plays a crucial role in 3D modelling. Visual programming software such as Grasshopper or Dynamo allows the generation of not a single solution but the design of a process that generates multiple solutions. The 3D reconstruction of architectural heritage enables the accurate reproduction, analysis, and preservation of historic structures. Scripting can automate tasks, generate visual representations, and manipulate data, allowing detailed modelling based on mathematical principles and relationships. This approach is similar to the principles used in historical architectural proportions. It also helps to understand, for example, ancient Roman architecture by recreating steps of dependencies in order principles.

Algorithm development enhances simulations by modelling processes such as weathering, structural fatigue, and material degradation over time. By simulating these processes, experts can predict how architectural objects might have transformed over the centuries, aiding in accurately reconstructing their original state (Barceló, 2000). Machine learning and pattern recognition techniques generate virtual reconstructions by analysing existing ruins and comparing them with documented data libraries, thus creating cohesive models of historical buildings (De Luca et al., 2011). Additionally, algorithms assist in assembling fragmented artefacts by matching segments based on patterns and geometries.

Level of Detail (LOD) is significant in architectural heritage simulations, as it balances the precision and complexity of digital representations with ethical considerations regarding reconstruction accuracy. Advanced algorithms manage and manipulate LOD, optimising computational efficiency while ensuring nuanced representations that are both authentic and accessible (Goetz et al., 2018). High LOD models achieved through laser scanning and photogrammetry capture intricate geometric and surface details, serving as reliable bases for analysis and further development of HBIM models (Banfi et al., 2022). The integration of scripting and algorithmic processes thus significantly advances the field of architectural heritage reconstruction, enhancing conservation efforts and educational applications (Mazzetto, 2024).

2. Case study

2.1. Triple-bay double arch of Musti

The presented monument is only a part of the research of the AFRIPAL project. It may seem of average interest and almost zero aesthetic value. However, structures that can be related to the Julian-Claudian period are rare enough in Africa to merit some attention (Mugnai, 2022).

Figure 2: Archive photo of triple-bay double arch of Musti, Tunisia. After Ferchiou, 1993, Africa XI-XII, ph. 4 p. 289.

The description, argumentation, and justification of the subsequent steps of the hypothetical reconstruction were carried out by Professor Naïdè Ferchiou on 44 pages in *L'arc double à trois baies de Mustis* (Ferchiou, 1993a). Briefing this description could omit some essential facts and arguments.

This paper focuses on the methodology of the work and the modelling techniques and methods. The presented workflow included LiDAR scans, photogrammetric models, algorithmic modelling, and Historic Building Information Modelling (HBIM), which were used to compare the resulting data with historical documentation.

2.2. Historical framework

Musti was a Roman city in the fertile Numidian and Roman African zone, close to ancient Carthage, which was destroyed in 146 BC. Musti is about 30 km southwest of Thugga – a UNESCO World Heritage site. The main research objective of the AFRIPAL project is to explore the dynamics of change in one of the two hundred cities that exist in the province of Proconsular Africa at a sensitive moment of transition between Numidian agglomeration and Roman city and to understand the development of Musti as part of the urban system of Africa and the Roman Empire between the 5th century BC and the mid-3rd century AD.

Using diverse methods, the project seeks a comprehensive understanding of the city and its neighbourhood. The resulting image may change our understanding of the colonisation and Romanisation of Africa. The project involves comprehensive prospecting, extensive environmental analysis, satellite imagery combined with traditional excavation methods and finds analysis and architectural virtual reconstructions of the sites to achieve this goal.

2.3. Gathering and study of the sources

The described arch is in the central part of the city Musti, about halfway between the two triumphal arches forming the city's ends. Next to the road that connected them is a paved square. Adjacent to it are two temples neighbouring the arch, which was the entrance to the perpendicular street leading towards the Forum.

Research (Ferchiou, 1993a) suggests that this area has been frequently redeveloped and altered due to its central location. It is challenging to study individual parts because, after Caesar, life continued throughout the imperial period, the Vandal period, and the Byzantine occupation. A large fortress from that last period was built in the upper city. The construction of the fortress destroyed many of the city's monuments, which were used as quarries. From an ornamental point of view, the collections are smaller, as the reliefs were often re-cut or hammered out.

Ferchiou described that "under present conditions, it is complicated to get an idea of the general appearance of the triple arcade. On the one hand, because of the late modifications that disfigured it, and on the other because of the early clearing of the site (c. 1958-60), with the result that we have not been able to determine exactly where this or that block was excavated."

The arch's construction occurred in the second quarter of the 1st century AD. As a separate structure, the arch existed until the rebuilding of the neighbouring temple (164-165 AD), when it was partially destroyed and incorporated as part of it. The 1993 study assumes a hypothetical reconstruction of the Roman Three-bay Double Arch before the temple was rebuilt.

During the research conducted in the 1990s, measurements and documentation of individual elements were carried out (Fig. 3). The first step was their analysis and understanding of the relationships. Finding and identifying these elements in the archaeological site was also challenging, as some were more than 100 m from the arch.

The problem that occurred here was the integration of different data and sources in one digital environment. In the described case, the inventory of objects and the information assigned to them was created as a database in Microsoft Access v. 2411, where each surveyed architectural object had its ID number entered in the Archicad 27 model as one of the properties of the individual objects. Unfortunately, Archicad has no direct connection to database programs such as FileMaker or Microsoft Access, so the information was assigned manually as properties. Considering the fact that during the AFRIPAL project, an inventory of more than 900 architectural objects was created, assigning that to the model would be time-consuming and should be optimised. Graphical data, such as drawings and photos, were added directly to the HBIM as images in 2D workspaces.

The next step was to verify historical documentation accuracy by comparing them with real-world dimensions and scanned elements. The documentation was compared with research conducted in 2022 and 2023 using LiDAR scanning, photogrammetry, and hand measurements. The linear scale, visible in almost all the drawings, provided a good starting point. However, due to the source of these drawings being a scanned PDF, it

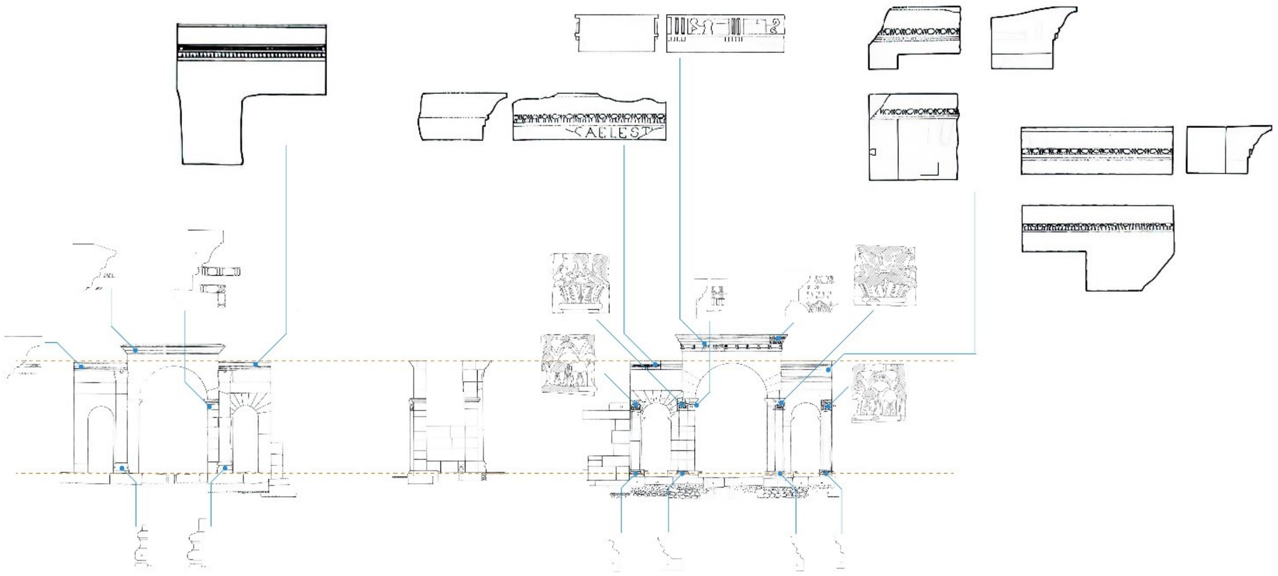


Figure 3: Professor Naïdè Ferchiuou's documentation, organised and aligned in Archicad for references. All the details in the drawing are scaled five times to enhance readability. After Ferchiou, 1993, Africa XI-XII, fig. 10,11,12,13,14,15,16,17,22,23,24,25,27

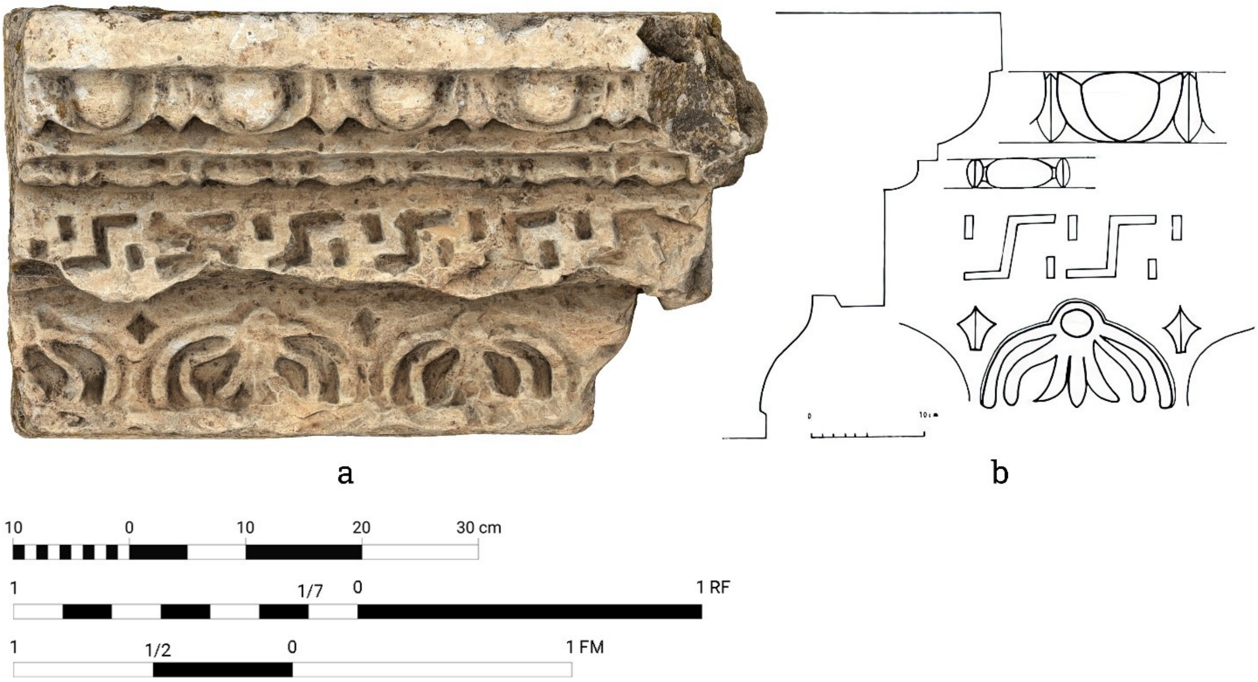


Figure 4: a) Photogrammetric textured model made with Reality Capture; b) after Ferchiou, 1993, Africa XI-XII, fig. 17b; p. 352; RF – Roman feet = 29.6 cm, FM – Ferchiou module = 24 cm.

could not be considered a reliable reference. Sometimes, the dimensional deviations resulting from the linear scale were about 14%. Therefore, all elements were remeasured manually and scanned using the Scaniverse 2.1.8 (Scaniverse, 2024) and Polycam 1.3.10 (Polycam, 2024)[1] applications on an iPad Pro to work on-site. That workflow allowed us to quickly collect primary data and work on the archaeological site in real time. The remains of the arch and all associated elements were scanned, measured, and photographed using a full-frame camera for later processing in photogrammetry software (details in Section 2.4.1). On-site processing was not possible due to hardware limitations. An example of comparing the resulting models and archive documentation can be seen in Figure 4.

[1] All scans were later reprocessed in newer versions of these applications - Scaniverse v. 4.02 and Polycam v. 1.3.9.

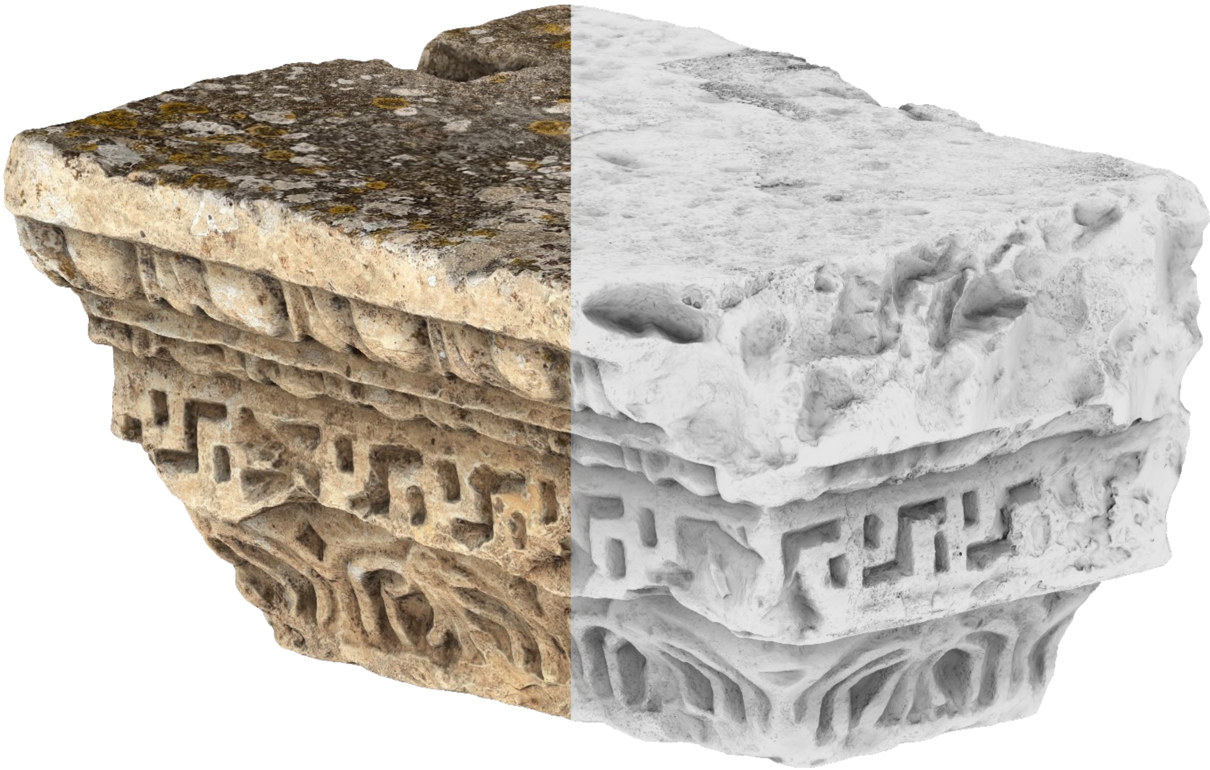


Figure 5: Cornice photogrammetric model with and without texture.

An important aspect of the virtual reconstruction considered was the measurement units. In her research, Ferchiou conducts a ratio analysis to find the module used to build the arch. She compared the metric dimensions from the site's survey with two systems of units – Roman feet and Punic cubits. Neither system fits the existing object; hence, she proposed a theoretical modulus between 24 and 24.5 cm without being possible to give preference to one of the two figures (Ferchiou, 1993b).

When working with historical objects, it would be ideal to introduce a custom unit system into the 3D software. In the case of many of the programs, like the Archicad 27, using a customised unit system is not possible. Rhino 7 allows that, but scaling errors were generated when exchanging data between the programs, as there was no direct conversion between the built-in and custom unit systems. However, considering the historical context and accuracy, a comparative analysis was conducted using Roman feet, and it was based on proportions and modularity rather than specific units.

2.4. 3D modelling

2.4.1. Photogrammetry

All the objects and architectural details mentioned in Ferchiou's article were scanned at the site. It allowed the creation of quick-to-process low-poly models for on-site work and verification of assumptions. Among other things, AR was used to check hypothetical assumptions by placing scanned elements in likely locations. Images were taken with a full-frame Sony Alpha 7R II (ILCE-7RM2) camera at 42 MPix resolution to create accurate photogrammetric models later. Reality Capture v. 1.3 was used to process the images, resulting in high-detail textured mesh models and dense point clouds.

For each architectural element (example in Fig. 5), 30-100 images were taken. As a result, models built from about 10 million vertices were obtained. They were then simplified to low-poly meshes with about 50000 vertices. It ensured fast file handling while maintaining high-quality textures.

More than 700 photos were taken of the remains of the arch gate (seen in Figs. 2 and 6). The high-detail model contained over 2 billion points and then was simplified to about 100000. While high-detail processing of such models accurately reflects reality, it does not allow for smooth operations due to their size and hardware requirements. In order to work quickly and efficiently in Archicad, it was necessary to decimate the point cloud. In this case, PointCab Origins 4.2 (PointCab, 2024) was used to decimate point clouds and generate drawings, which were used as documentation and trace references for modelling. There are also free tools for creating photogrammetric models, such as Meshroom v. 2023.3.0 (AliceVision, 2024) and Cloud Compare v. 2.13.2 (Girardeau-Montaut, 2024).

The question that may arise is why the mesh model from RealityCapture v. 1.3 (Capturing Reality, 2024) was not used directly. Due to the complex history and numerous rebuilds of the arch, object-oriented modelling was necessary to assign additional parameters and information. The idea was to model in BIM software where additional information could be assigned to individual objects. Another assumption was to use visual programming to create a process instead of one variant of virtual reconstruction and to be able to test different solutions quickly.

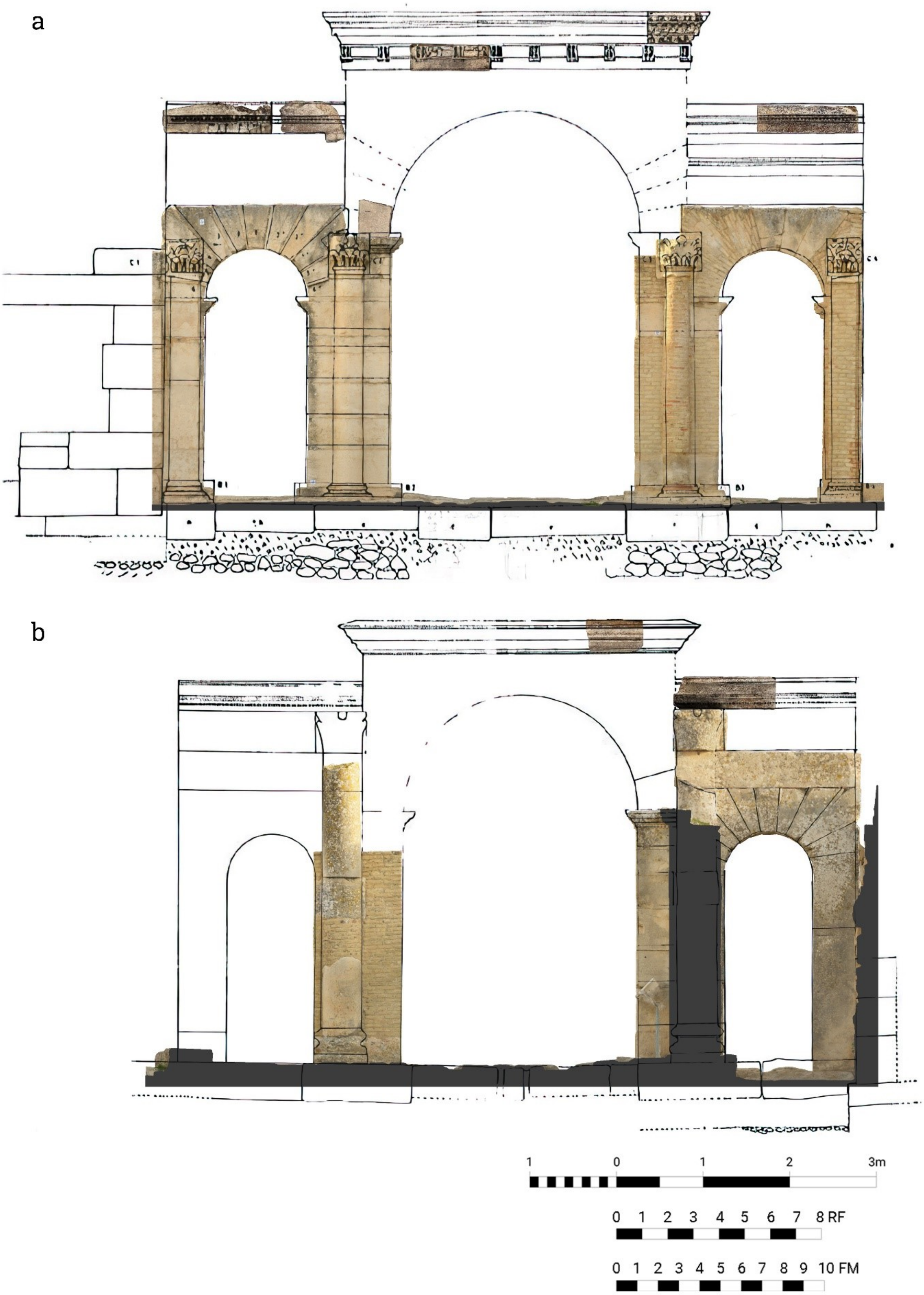


Figure 6: Virtual anastylosis of scanned elements overlayed on Ferchiou's drawings with hypothetical reconstruction (after Ferchiou, 1993, Africa XI-XII, fig. 7, 22); a) south elevation; b) north elevation; RF – Roman feet = 29.6 cm, FM – Ferchiou module = 24 cm.

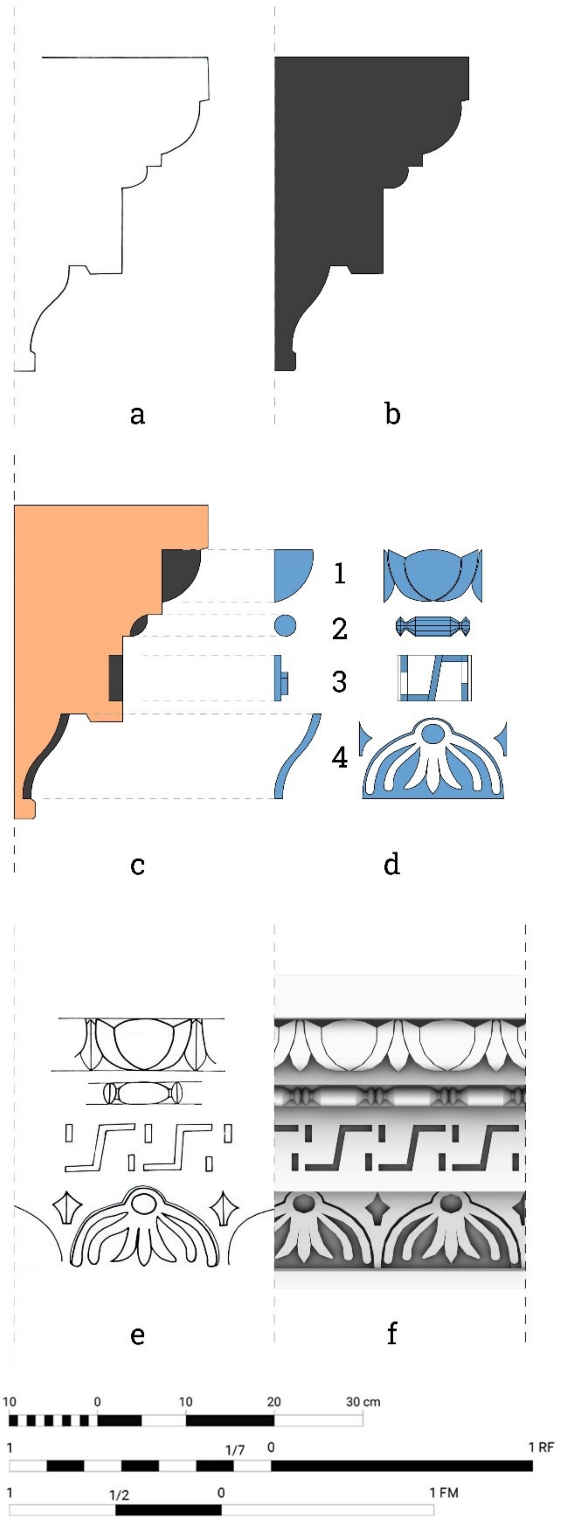


Figure 7: Process of BREP parametric modelling of details: a) cornice section from archival documentation (after Ferchiou, 1993, Africa XI-XII, fig. 17b; p. 352); b) complex profile created in Archicad; c) profile breakdown into separate components; d) separate mouldings in section and elevation 1) ovolo, 2) astragal beads, 3) pearls and pirouettes, 4) heart stripes; e) cornice elevation from archival documentation (after Ferchiou, 1993, Africa XI-XII, fig. 17b; p. 352); f) elevation of 3D modelled cornice; RF – Roman feet = 29.6 cm, FM – Ferchiou module = 24 cm.

ArchiCAD 27 (Graphisoft, 2024) and Rhinoceros 7 (McNeel & Associates, 2023) with Grasshopper and ArchiCAD-Grasshopper Connection were selected software. That set provided a workflow connecting HBIM modelling capabilities, teamwork, and algorithmic processing.

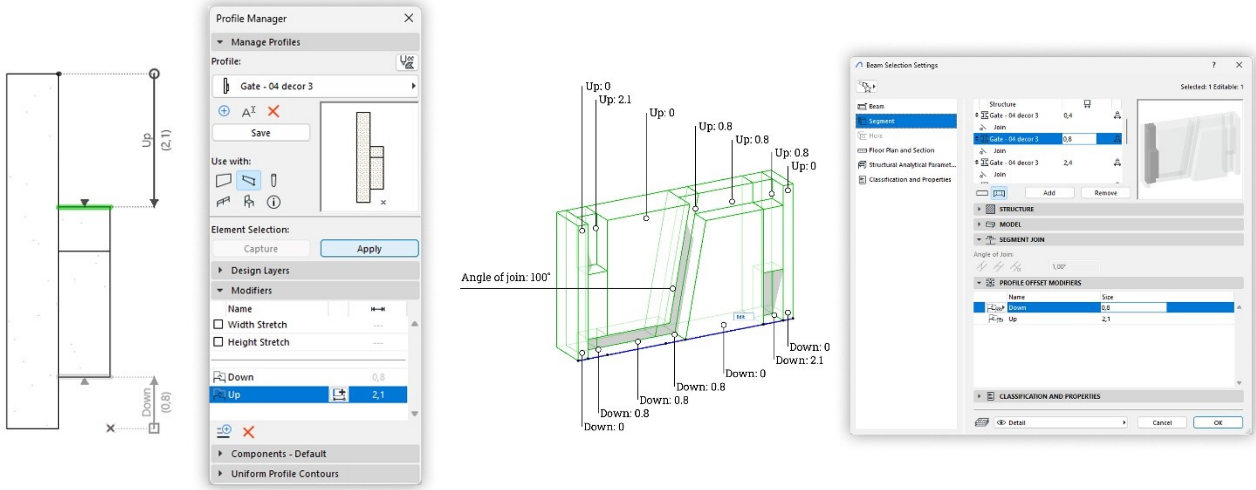
2.4.2. Parametric modelling

Modelling in Archicad 27 was based on the collected documentation and references in the form of a point cloud. The vectorised profiles of individual elements served as Complex Profiles in the software and were extruded as columns and beams.

Modifiers in the Complex Profile tool and segmented beams and columns in Archicad were used to achieve greater accuracy in the details modelling. The cornice fragment (Figure 5) was the most complicated element to model; hence, it will serve as an example of the techniques used.

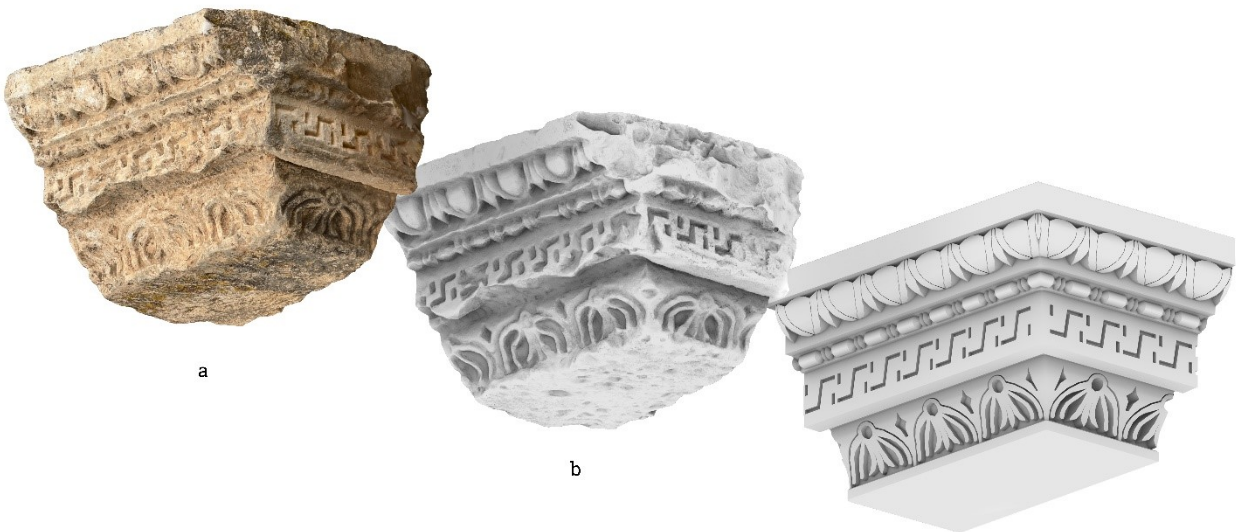
The profile (Fig. 7a) came from documentation from the 90s and was verified with actual dimensions. Based on this, a vectorisation and a profile were created in Archicad (Figure 7b). The modelling of the details required splitting the profile into parts – fixed (Figure 7c in orange) and varying (Figure 7c in black). Each moulding (Figure 7d.1-4) required a different modelling technique.

- Ovolo (Figure 7d.1) – a beam was created using the profile. Then, beams based on the silhouette from the front view were created perpendicularly. The elements thus created were intersected in Boolean operation.
- Astragal beads (Figure 7d.2) – This detail was modelled using the beam tool. An extension of this tool was used to allow the creation of segmented beams. The main parameter was the circle's diameter, which changed in successive segments of beads. The module thus obtained was then multiplied along the length of the entire element. Another solution would be to create a single object with the appropriate length of the number of segments, but creating such a list in the Beam tool is very time-consuming and labour-intensive.
- Pearls and pirouettes (Figure 7d.3) – This rather complicated shape also used the beam tool, where modifiers were added to the base profile, which extended the element's Top and Bottom. With the segments using modifiers, a module was created that was further duplicated. As with the first element, thanks to the modifiers, it would be possible to replicate reality more accurately, still using the same profile and changing only its parameters - the schema of how each parameter and segment works is shown in Fig. 8.
- Heart stripes (Figure 7d.4) – A similar method to the first detail, except that Subtraction was used instead of Intersection.



a b

Figure 8: Process of modelling using a segmented beam with modifiers: a) section of the created profile with applied modifiers “Up” and “Down”; b) segmented beam created with the profile with different modifiers values and connection angles in segments.



a b c

Figure 9: a) Textured photogrammetric model; b) Photogrammetric model without texture; c) BREP model.

All profiles were created as parametric. In the case of modular elements, the Width Stretch parameter allows for expansions of a given module. If the precision of a digital reconstruction were a key element, it would allow for the accurate reproduction of reality. In that case, the pearls and pirouettes modules were not always the same, but a single-size module was used to simplify modelling. This method’s model (Figure 7f) was compared with archival documentation (Figure 7e) and a textured mesh model. In order to avoid skewing the geometry by texture, white models were used as the basis for comparison (Figure 9).

The analogous modelling method was used to model the rest of the existing elements to represent the geometry (Fig. 10). This is especially important when verifying specific hypotheses based on the analysis of proportions or similar dimensions. Some did not require individual profiles, and basic modelling tools were sufficient. The same profiles and modelling techniques were used to digitally recreate the missing parts in this hypothetical reconstruction. Through virtual anastylosis, scanned existing parts were placed into their hypothetical original position (Fig. 11) based on Professor Ferchiou’s hypothesis.

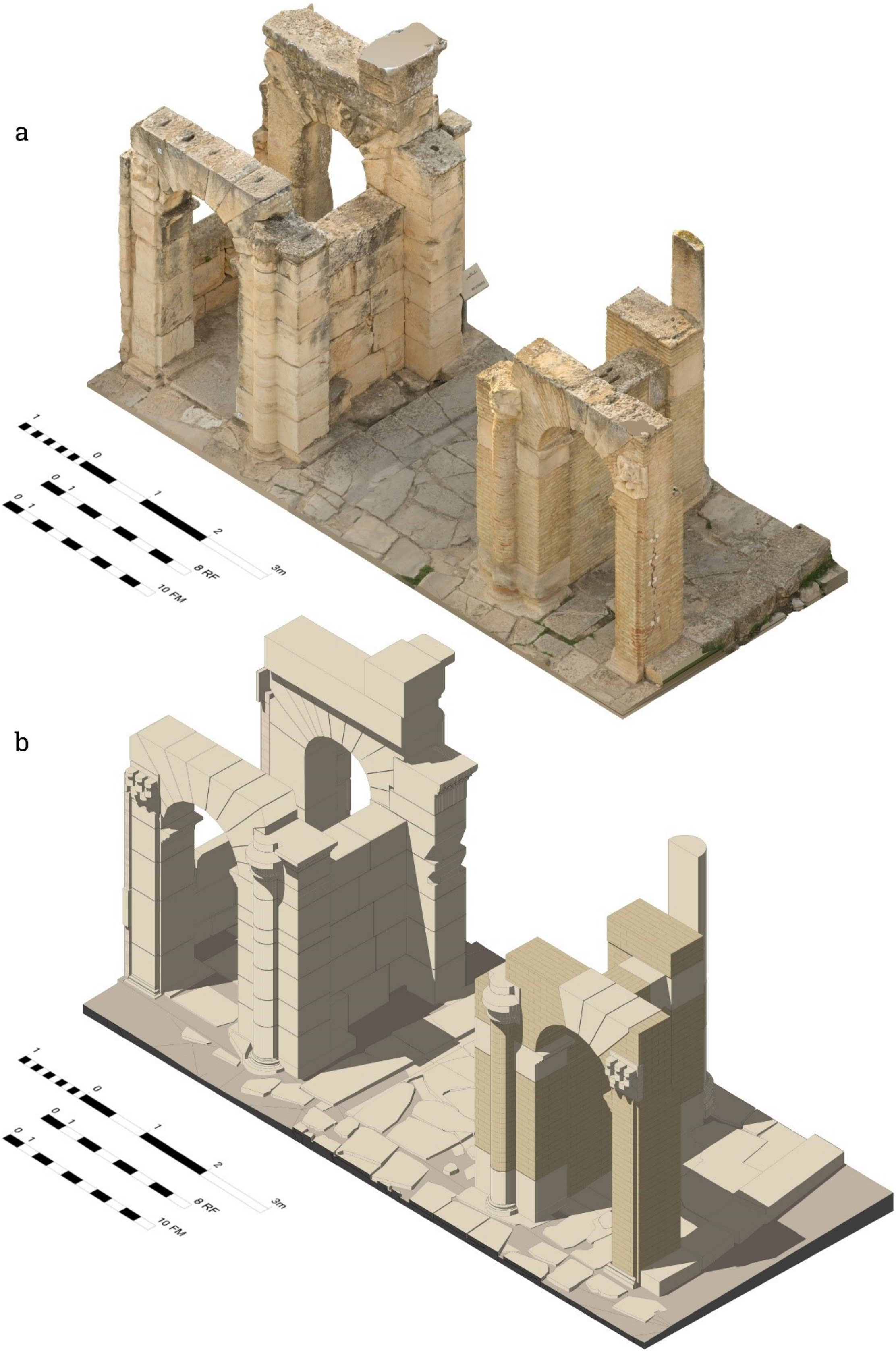


Figure 10: a) Photogrammetric textured mesh model; b) Archicad HBIM object-based model; RF – Roman feet = 29.6 cm, FM – Ferchiou module = 24 cm.

Figure 11: Virtual anastylosis on virtual reconstruction.

2.4.3. Algorithmic modelling

Prof. Ferchiou described her hypothetical reconstruction as only one of the possible variants. She describes that the particular architectural elements and details she used did not necessarily belong to this building. They were used because of their approximate dating and style of decoration.

In the presented case, computational modelling was used as an experimental approach to check different possible options. The algorithm used previously modelled objects, information, profiles, geometries, and modifiers from Archicad to create other variants of Musti's triple arch gate in real-time. Utilising Rhinoceros with Grasshopper and Archicad-Grasshopper Connection, the team could customise the overall height and width, height of cornices and friezes, curvature of the middle arc, the height of the arches connecting walls, covering or lack of it; according to chosen parameters. The variants shown in Fig. 12 illustrate the possibilities by being geometrically correct by following an assumed system of proportions derived from Roman feet and modularity; hence, not every value was possible, but only those that fit into this scheme. At this stage, they lack a critical view, such as that of an architecture historian, confirming or denying possible solutions.

This approach addresses the challenges of recreating uncertain ancient architectural forms by providing flexibility and adaptability in the design process. Although the team has not gotten a fully working and modifiable model because of the number of possible solutions hidden in the details, it highlights the potential of modern computational techniques in digital archaeology and architectural heritage studies. Many objects at this point cannot be created as parametric using Grasshopper-Archicad Connection because this tool does not allow for at least the creation of segmented columns and segmented beams, the essential tools in the case described above. Algorithmic modelling served as a tool to speed up the process of modelling Ferchiou's hypothesis-based reconstruction. As a process, it allows for many more possibilities and should be explored separately.

Given all the unknowns and hypotheses described by Prof. Ferchiou, the entire gate reconstruction should be shown in an interactive form, allowing the user to check possible variants, systems of proportions and modules and relationships between elements. The experiment was carried out to create other variants of the arch in order to show that this virtual reconstruction, based solely on Ferchiou's assumptions, is not the only possible one.

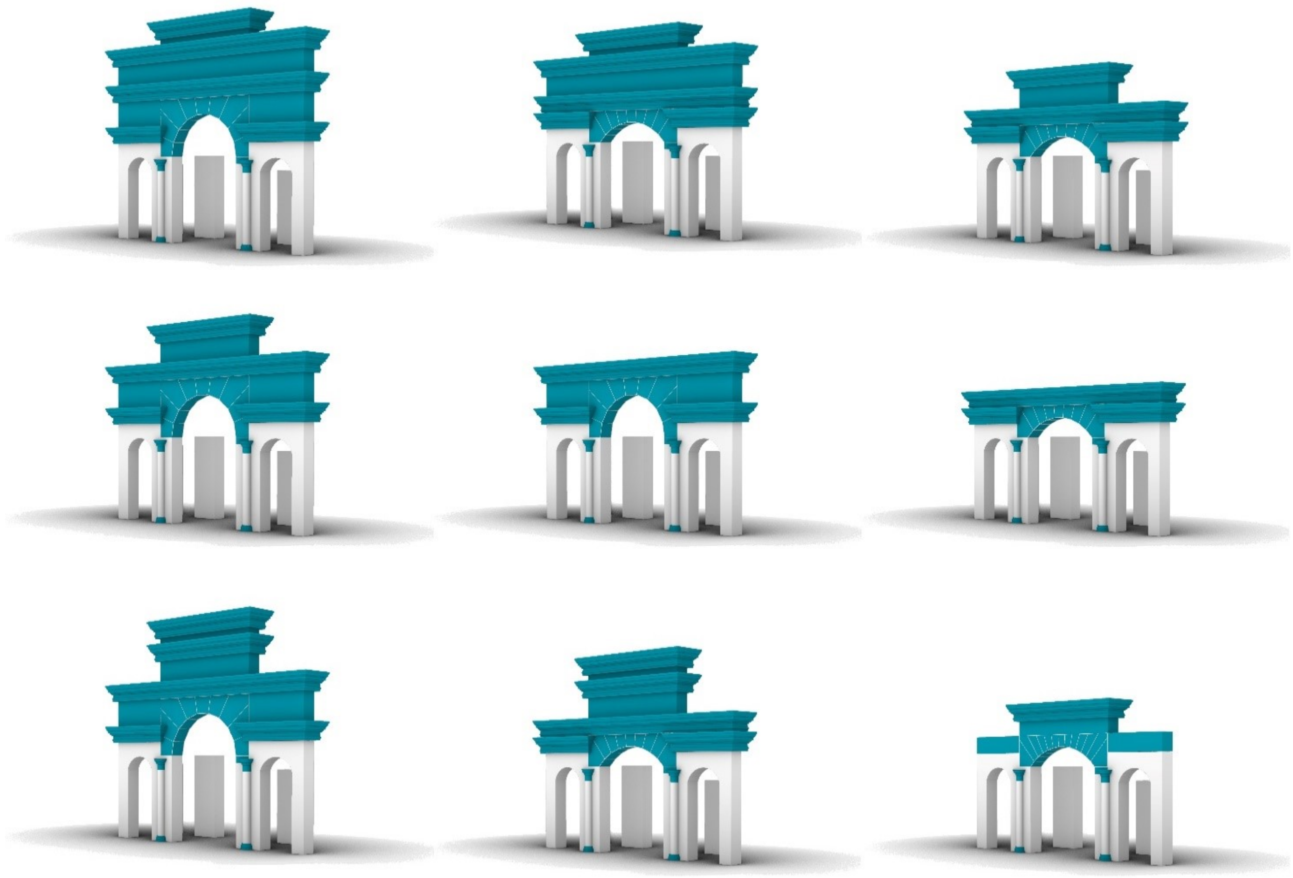


Figure 12: Algorithmic variations of the arch elements.

2.5. Visualising results

In the case of the arch from Musti, the visualisation consisted of creating static raster images. One is a photorealistic visualisation (Fig. 13), rendered in Archicad 27 and the photography superimposed on in Adobe Photoshop 2024.

The other was to show the various stages and characteristics of the virtual reconstruction. Each modelled element had a classification assigned to it, assigning whether the element is preserved in its original state, reconstructed, is anastylosis, virtual anastylosis, or virtual reconstruction. Properties were used to create graphic variants and overwrite existing textures based on them. The result is a visualisation (Fig. 14) highlighting the abovementioned issues.

Figure 13: Photorealistic visualisation

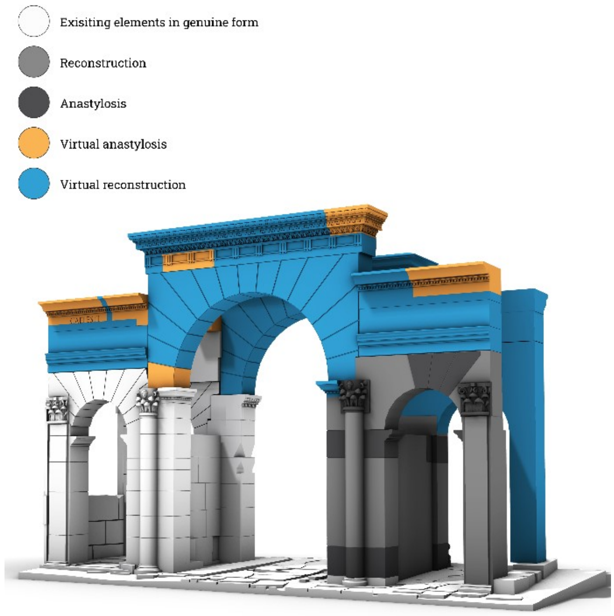


Figure 14: False-colour visualisation of various aspects of virtual reconstruction

3. Discussion

The case presented anticipated and unexpected challenges, highlighting the importance of integrating advanced technology with historical documentation. Accurate modelling of historic structures is a complex yet vital endeavour that combines advanced technology with interdisciplinary collaboration. By embracing these technologies, professionals can create precise and faithful models that not only aid in the conservation of historic buildings but also enhance our understanding and appreciation of architectural heritage.

The challenge of built heritage modelling is being studied by various researchers (Yang et al., 2020). The process calls for a balance between precision and practicality, which must be evaluated on a case-by-case basis. Many cases like (Alshawabkeh, Baik, & Miky, 2021; Poloprutský, 2019; Visintini et al., 2019; Diara & Rinaudo, 2019; Barazzetti, 2016; Quattrini, Malinverni, Clini, Nespeca, & Orlietti, 2015; Garagnani & Manferdini, 2013), connected to Scan-to-HBIM methodology show similar methods of achieving the HBIM models based on Terrestrial Laser Scanning (TLS) and/or photogrammetry. They are based on BREP, Non-Rational B-spline (NURBS), or MESH geometries assigned as architectural objects as part of libraries in BIM software. If these objects are not parameterised, they remain usable only in one case and cannot be edited afterwards. Parametric dependency of individual parts of the geometry allows them to be reused or, in the case of modelling irregular elements, to use the same one with different properties. However, this does not solve the problem of creating custom objects with each case.

This paper shows a different approach to detail modelling. The described case uses only native Archicad tools and elements by enhancing them with custom parameters (Archicad's modifiers). It proves that complex geometries can be modelled without custom libraries.

Further research (Croce, Caroti, Piemonte, De Luca, & Véron, 2023) discusses applying Artificial Intelligence (AI) methods in the semi-automatic reconstruction of HBIM models in Revit from point cloud data. Research shows that Grasshopper supports parametric modelling of complex and irregular architectural components. AI automates the classification and reconstruction of building components, speeding up the Scan-to-BIM process. Another research (Gil, Arayici, Kumar, & Laing, 2024) critically reviews the application of Machine Learning (ML) and Deep Learning (DL) in HBIM, emphasising that the manual process of converting reality capture data into accurate models is time-consuming and error-prone. The authors highlight the potential of ML and DL, especially in automating point cloud segmentation and classification, to streamline this process. Despite promising advancements, the paper emphasises ongoing challenges and the need for further research to fully leverage ML and DL in cultural heritage projects.

Considering the possibilities of automation, the method described in this paper can be used later with the development of automation processes. The project's use of parametric and algorithmic modelling (Fig. 12) underscores the potential of these techniques for reconstructing the past and real-time exploration of alternative variants.

Regarding the visualisation of the arch reconstruction results, photorealistic visualisation (Fig. 13) can be misguiding and, aside from a nice picture, does not show any valuable information, much less the reasoning behind the reconstruction. A virtual reconstruction presentation should allow for examining multiple variants, if any. The ability to test multiple hypotheses through virtual modelling has broad implications for understanding and interpreting historic structures, providing a more dynamic and flexible approach to architectural reconstruction.

Relating to the work by Prof. Ferchiou, the presented 3D reconstruction coincides with her hypothetical elevations of the structure (Fig. 6). It confirms the hypothesis she proposed but does not solve all the unknowns. A virtual anastylosis of the individual scanned elements (Fig. 15) highlights these uncertainties. The dimensions of cornices A, B, and C (Fig. 15) correspond to the longitudinal axes of the individual arches and the axis of element D. This suggests two possible solutions. One, following the current hypothesis (Ferchiou, 1993), where there was no covering between the arches, so then a decorated cornice could have appeared there. The other, resulting from the alignment of the elements with the axis, may suggest that the two arches were connected and the archway was roofed. Moreover, cornice B and the L-shaped part of it may indicate that it was part of a corner and that the right side of the gate was also built up. Verifying this solution would require additional on-site research. The results may lead to a change in the name of the titular Double Arch.

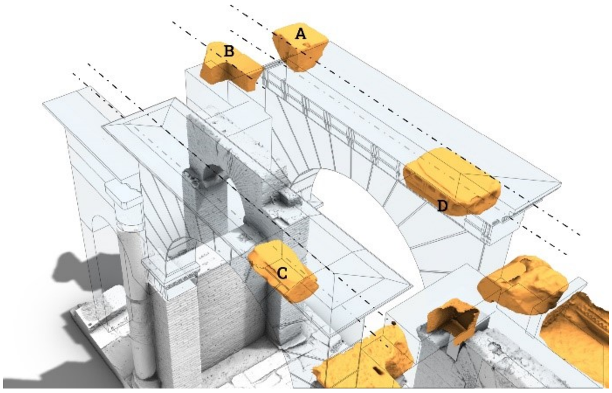


Figure 15: Visualisation of virtual anastylosis of individual elements with axes derived from the dimensions.

4. Conclusion

The virtual 3D reconstruction of the Roman three-bay double arch of Musti in Tunisia showcases the transformative potential of integrating advanced digital tools and interdisciplinary methodologies in the architectural heritage field. Employing modern technologies such as HBIM, algorithmic design, LiDAR scanning, and photogrammetry, the study achieved accuracy and detail in recreating the arch's hypothetical original structure. Algorithmic modelling and parametric tools facilitated the testing of reconstruction variants and accelerated modelling of complex components, offering flexibility and adaptability in addressing uncertainties inherent in historical reconstructions.

This work emphasises the importance of interdisciplinary collaboration, combining the expertise of archaeologists, architects, and digital specialists. It also demonstrates the educational value of using practical case studies that introduce students to an emerging field combining programming and architectural heritage.

The presented workflow combines virtual anastylosis and interactive reconstruction techniques. It also responds to the challenge of integrating various historical and contemporary data sources and establishing a solution for future virtual reconstructions. The research recreates the ancient Roman monument by combining historical documentation with modern technology. It develops our understanding of it, showing that Prof. Ferchiou's proposed solution should be re-examined with additional on-site research.

Despite challenges like high equipment costs and data integration complexities, the study highlights the need for ongoing innovation and collaboration to ensure the accessibility and reproducibility of virtual reconstructions. This work paves the way for further exploration in virtual archaeology, reinforcing the role of digital tools in preserving cultural legacies for future generations.

The issue that should be addressed in future work is how to publish the results, considering the argumentation behind the virtual reconstruction. This is particularly relevant when using existing databases and archival hypothetical reconstructions that exist only in text form and as 2D drawings and are digitally reconstructed.

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