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Two methodologies for the virtual reconstruction of the architectural remains of a Late Roman archaeological site based on the 3D point cloud

This paper presents and discusses two approaches to the virtual reconstructions of the architectural remains of the Late Roman site of Umm-al Dabadib, at the outskirts of the Kharga Oasis (Egypt’s Western Desert). The dense settlement is clustered around a central building resembling a fortlet. The primary construction material was mudbrick, completed by a few stone elements. Elliptical pitched-brick barrel vaults covered the small rooms that compose the various buildings. The unit of measurement used in the planning and building was the ancient Egyptian (reformed) cubit. The first method adopted to study these remains consists of direct 3D modelling on the photogrammetric point cloud using the parametric approach of the BIM software Autodesk Revit. This process allowed the complete reconstruction of all levels of the well-preserved fort in the settlement center. The second method tested, on the domestic unit in the northwest corner of the settlement, involved 3D modelling of hypothetical original form starting from 2D technical drawings elaborated from the photogrammetric point cloud in its current state and its hypothetical original form. These drawings were used as a reference to model the domestic unit in Rhinoceros software, which is more suitable to model complex shapes, such as typical living room of the local domestic units, covered by two intersecting barrel vaults of different sizes. The complex morphology of the biaxial vaulted system would have been difficult to model with a more rigid software such as Revit. Instead, Rhinoceros allowed recreating the biaxial vault using tools to extrude profiles, subtract and add simpler shapes. The photogrammetric model was used to adapt the reconstruction to accurate measurements.

Keywords:
Photogrammetric point cloud; Modular modelling; Digital reconstruction; Late Roman settlement; Architectural classification

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1. INTRODUCTION

Digital surveys, both image- and range-based, allow an efficient 3D and 2D representation of the actual state of an archaeological site and its architectural remains. 3D data, captured with a photogrammetric and/or a laser scanner method, record and store a large amount of details of the measured scene (Alshawabkeh et al., 2021). The final point cloud containing all the metric and eventually radiometric information acquired on that moment may be used in different ways: first of all, it may be consulted at any time; then, 3D models can be easily visualized, managed and measured even by non-expert users through simple software or even online portals; classic technical drawings, 3D models (Barni et al., 2020) and innovative architectural stratigraphic analysis (Brusaporci at al., 2019; Nobles and Roosevelt, 2020) can be elaborated after a careful interpretation of the metric data; finally, the survey data can help understand the original aspect, form and function of the archaeological remains and develop 3D reconstructive hypotheses (Guidi et al., 2014).
Moreover, the analysis of the metric and geometric models and their comparison allow to highlight and identify formal/ideal models (Bolognesi and Stancato, 2021) and their variations in shape (Spallone et al., 2021). Finally, virtual reconstructions can also be a tool to model the various transformations that are no longer visible over the time (Santagati et al., 2020). The aim, in this case, is some sort of reconstruction of the memory of the place (Campofiorito and Santagati, 2020). The formulation of the geometrical hypotheses must be guided by the survey of the current state and by an analytical study of the historical sources (iconographic, bibliographic, etc.).
In this scenario, this paper presents and discusses two approaches to develop virtual reconstructions, that have been tested on the architectural remains of the Late Roman settlement of Umm-al Dabadib, located at the outskirts of the Kharga Oasis, in Egypt's Western Desert (Rossi and Ikram, 2018: 205-317) (fig. 1). The site, well-preserved thanks to the hyperarid climate and the virtual absence of human activities since its abandonment in the early V century AD, has been inaccessible since 2016 for security reasons. This situation prompted the research group dedicated to the study of this site to look for alternative solutions to retrieve fresh information, that included making extensive use of satellite images and working remotely on the available data (Rossi et al., forthcoming). The methodologies presented here are part of this research project.

2. THE CASE-STUDY

The site of Umm al-Dabadib consists of two settlements, one dating to the Early and one to the Late Roman Period, accompanied by a vast agricultural system and a scatter of cemeteries. It is likely to have functioned as water station along the ancient desert track currently called Darb Ayn Amur well before the Roman Period, but it is currently difficult to establish the extent of the earlier settlements (Rossi and Ikram, 2018: 551-9). The object of the current study is the Late Roman settlement, named 'Fortified Settlement' (fig.1), founded at the beginning of the IV century as part of a large-scale

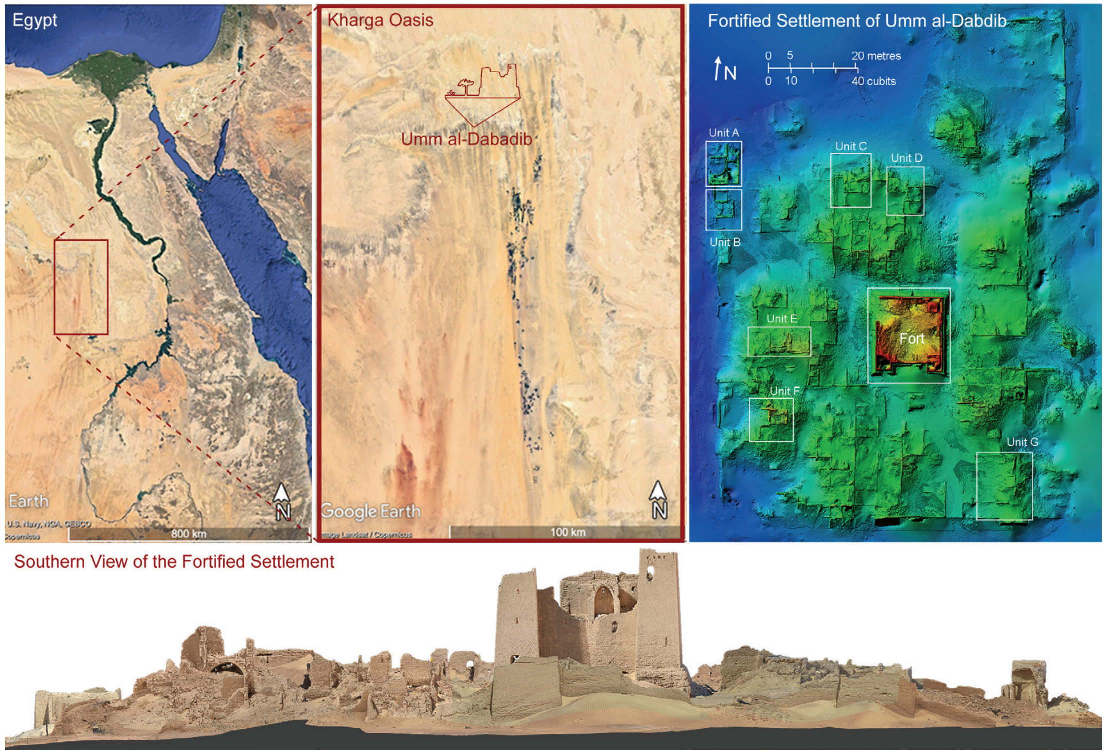

Fig. 1 - Position of the Fortified Settlement of Umm al-Dabadib. To the right, the Digital Elevation Model of the whole site and below its southern orthoimage.

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programme meant to harness the strategic and commercial potential of the Kharga Oasis (Rossi et al. forthcoming).
The archaeological remains of the settlement consist of a dense, geometrical mass of domestic units clustered around a central building, named the 'Fort' because of its sturdy appearance. Figure 1 shows, to the left, the position of the Kharga Oasis within Egypt; in the middle the position of Umm al-Dabadib within Kharga; to the right the Digital Elevation Model of the Fortified Settlement and below the southern orthoimage of the settlement. The northern orthographic view of the Fortified Settlement photogrammetric point cloud is shown in figure 2. The photogrammetric acquisitions and the related topographic network of the entire area was carried out during the 2014 on-site campaign (Fassi et al., 2015), whilst the 3D digital survey of the accessible inner spaces of the Fort took place on the following year (Rossi 2018).
Figures 1 and 2 include the two buildings that are the subject of this paper, the Fort in the centre and the domestic unit labelled A in the northwest corner. In the same images, more domestic units can be seen inside the site. Within the settlement, among the geometrical mass of vaults, a total of seven domestic units have been identified, thanks to the presence of their typical living room, covered by a biaxial vaulted system. Other domestic units are very likely not distinguishable because they are submerged by sand or collapsed.
Unit A is relatively well-preserved and lies exposed along the western edge of the Fortified Settlement. The other domestic units emerge from the mass of debris that constitute the remains of the settlement; their lower levels are probably well preserved, but they are currently invisible and part of their layout can only be indirectly inferred. In general, it is possible to say that the domestic units were all endowed with the same peculiar living room, accompanied by a combination of vaulted rooms of different heights, served by a staircase resting on rampant arches. The kitchens are likely to have been placed on small rooftop terraces (Rossi and Ikram, 2018: 225-36). The main construction material was mudbrick, with the addition of a few stone elements; the small rooms that compose the various buildings were all covered by elliptical pitched-brick barrel vaults (Rossi and Fiorillo, 2020). Figure 3 shows a typical and well-preserved barrel vault in the northeast corner of the unit A.
The unit of measurement used in the planning and building phases was the ancient Egyptian (reformed) cubit (Rossi and Fiorillo, 2018), detected also in the design of the contemporary forts belonging to the same strategic programme. The presence of the ancient Egyptian unit of measurement in the planning and building of settlements built to implement the Roman strategy of control of the southern border of the empire poses a number of questions on the identity of the strategists and the builders of these sites and makes it even more important to investigate their design and layout (Rossi, 2019).
The well-preserved Fortified Settlement of Umm al-Dabadib offers a unique chance to study the three-dimensional composition of the constructions. Its main advantage, however, is also its main disadvantage: the surface is easy to read and the overall layout is clear, but most of the buildings lie anyway under a thick layer of debris, preventing any clear understanding of what lies beneath. Excavation might solve at least some of the existing doubts, but would not be resolutive as clearing vast portions of the settlement would be a challenging enterprise in that remote and hostile environment. Even if it were possible, it would not necessarily represent the only and optimal method to investigate the overall three-dimensional

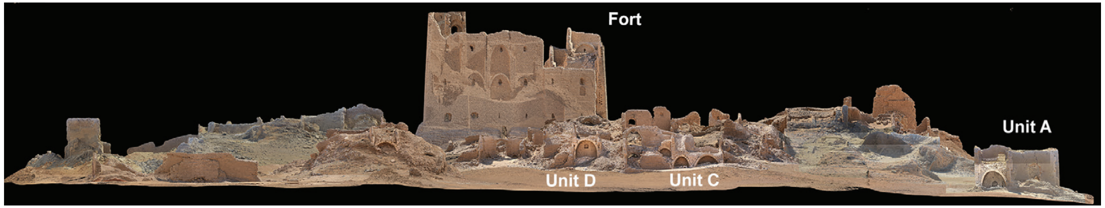

Fig. 2 - Photogrammetric point cloud of the Fortified Settlement seen from North. The Fort rises in the middle and the domestic Unit A, located on the northwest corner, is visible to the right.

Fig. 3 - Panoramic image of the site seen from north, with the domestic Unit A in the forefront and Fort in the background.


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organisation of the settlement. The best solution is to adopt a combination of the results of physical investigations and digital reconstructions based on the available clues (Fiorillo et al., 2020).
Moreover, although advanced survey and representation techniques are widely used in the archaeological field, it is still complicated to directly relate the 3D models to all other available information, both metric and geometric (Dell'Unto et al., 2016). However, this is a fundamental aspect to develop reconstructive hypotheses and define theoretical reference models (Demetrescu and Ferdani, 2021). In particular, parametric modelling is proving especially useful to achieve significant results (Fiorillo and Rossi, 2021), and represents the foundation of the study presented here.

3. METHODOLOGY

The study presents two procedures of reconstruction applied to two buildings differing in terms of form, dimension and function: the Fort (in the centre of the Fortified Settlement) and the domestic Unit A (located in the northwest corner of the Fortified Settlement). Both methods fall within the reality-based modelling approach, as they are based on the photogrammetric survey of the archaeological remains (Spallone et al., 2019). The geometrical modelling of existing heritage may be even defined as a reverse engineering process (Barba et al., 2021).
The geometrical model of the Fort was recomposed using direct 3D modelling on the photogrammetric point cloud in a BIM environment. The 3D geometry of the domestic unit was instead reconstructed starting from the two-dimensional drawings, extracted from the photogrammetric model. The point cloud has always been kept as a reference during the solid modelling of the geometries to check the coherence between the measured entities and their modelled twin.
In both cases, the virtual reconstruction of the building was developed according to the following steps: acquisition of metric and architectural data, architectural semantic decomposition, geometrical modelling of measured parts and reconstruction of the missing or buried parts.
The study and interpretation of the visible and measurable remains are based on analysing all available types of archaeological and historical documentation and survey output: old and recent photos, direct measurements, sketches, as well as digital 3d models. The final result is a first interpretation of the building, based on the largest possible amount of metric information.
After this essential phase of acquisition of data, a semantic decomposition of the visible and measured architectural elements may be implemented: in our case studies, the elements that were identified as fundamental are the walls and the two types of elliptical vaults, the pitched-brick barrel vault and the biaxial vault. The architectural semantic analysis is fundamental to understanding the spaces and allow a correct simplification of the details for the transition from the real (detailed point cloud) to the geometric model (Guadagnoli et al., 2021).
The subsequent step consists of geometrically modelling the elements of which the measures are known. The 3D geometry is modelled according to a module corresponding to the ancient unit of measurement that was used in the construction of these buildings (the cubit), which helps to schematize the layout of shapes and spaces. In the final phase, the architectural/geometrical elements that were modelled (mainly vaults), can be adapted to their partly visible counterparts and repeated within the rests of the settlement, and can thus be used for the virtual reconstruction of the partly-buried buildings.
It must be emphasized that the operation of the geometric modelling has often raised new questions and uncertainties concerning the initial interpretation of the space and volumes. In particular, the metric and geometric comparison between the ideal reconstruction and the metric reference (the point cloud and its products) often produced new doubts. Therefore, in order to obtain satisfactory results, it has often been necessary to re-study the context, revise the evidence and look for further information on the building and possibly refer to similar cases in the same geographic area, thus temporarily going back to a phase of collection of further and fresh information. The theoretical order of the phases is logical and efficient, but it is not linear: it could rather be defined as circular.
In conclusion, the two methodological approaches share the same theoretical workflow and the same steps. But in practice, the geometrical modelling is performed in two different ways.
Finally, we would like to stress that the reconstruction does not replace the survey model of the current state. Both models are complementary but not alternative for the study of form and function of the archaeological remains. Moving from the point cloud to a 2D and 3D representations requires a minimum schematisation, thus slightly detaching the model from the reality. At any rate it is an extremely useful tool for the interpretation of the original architectural structure and layout.

4. THE VIRTUAL RECONSTRUCTIONS OF THE FORT

The first method investigated for the digital reconstruction of the Fort consists of direct 3D geometrical modelling on the photogrammetric point cloud using the implicit BIM environment of the software Autodesk Revit.
The Fort consists of 5 (visible and certain) levels of vaulted rooms distributed along the four sides of an internal courtyard. The shape of the last level is unclear, and might have consisted, at least partly, of a terrace. The central part of the building has completely collapsed, but partial remains or faint traces of the vaults on the upper floors are still visible. The ground floor probably consists of 16 vaulted rooms, 8 of which have been explored and surveyed (direct measures, photographic documentation, topographic and photogrammetric measurements could thus be used in the elaboration presented here). The same layout and distribution of the rooms seem to be repeated on the other floors, as confirmed by the survey on the first floor (that involved two accessible and well-preserved vaulted rooms) and the traces of the vaults on the perimeter wall on the upper floors. From a constructional point of view, the barrel vaults

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covered rectangular rooms, with the arch (actually the elliptical-shaped generatrix) of inclined bricks resting on the short side. As for the perimeter wall, the collapse of the west façade made it possible to identify a masonry layout of 5 headers (about 88 cm) at the lowest level, which tapers upwards until it reaches two headers (about 34 cm) on the fifth level (Rossi and Fiorillo, 2018: Figure 8). The internal dividing walls seem to be almost always one cubit (about 52 cm), equal to 3 headers. This metric data was verified in several portions of the Fort through direct visual inspection and on-site measures, photos and point cloud measurements.

The building photogrammetric model can be managed directly in the BIM work environment recognizing each point as a snap and taking direct measurements. Moreover, floorplans, elevations and sections can be generated to interpret survey data and model better the geometries. For example, the vault used to extrude its solid shape was drawn from a section of the point cloud.

The interpretation of the survey data and the ensuing metrological studies made it possible to establish that the inter-floor high is 2.6 m, corresponding exactly to 5 cubits. This metric information was used to define the reference levels and grids in the modelling software, which were essential to identify the planimetric position and elevation of the various architectural elements, even in areas of the building for which no measurements were available.

The various building components (walls, vaults, floors and stairs) were modelled individually, adapting to the point cloud and implementing an operation of extrusion. Once the architectural envelope was defined, the openings (doors and windows) were modelled as subtraction of volumes from the solid masonry.

By integrating the architectural information which is present on the different levels with archaeometric studies, it was possible to develop a first hypothesis concerning the distribution of the internal spaces. A total of 13 well-preserved vaulted rooms were modelled. The same modular geometry was repeated, adapting them to the visible remains, the possible distribution scheme and the cubit measures.

This process allowed to develop a complete reconstruction of all levels of the Fort (fig. 4-5). Modelling all levels implies address points that were still obscure: one of the most interesting concerns the internal circulation of all the levels, apart from the ground floor. Access to each level took place from the staircase located in the south-eastern tower, but then it is unclear how access was actually gained to each room, that is, whether they were all connected with one another (unlikely and uncomfortable, but not impossible) or whether they were served by a corridor, carved out from the space of the rooms along the central void (in this way thus substantially reducing the available space). Another possibility was that the rooms were served by an external corridor, supported by an additional structure grounded in the central courtyard. This solution had been deemed the most likely (Rossi and Ikram, 2018: 442-4): the necessity to further investigate this issue represented one of the triggers of the experiments to apply the concept of parametric modelling to the survey data.

5. THE VIRTUAL RECONSTRUCTION OF UNIT A

The second method was tested on the virtual reconstruction of the domestic Unit A in the northwest corner of the settlement. It involved 3D modelling based on two-dimensional technical drawings. The building consists of at least two levels (the presence of a subterranean level cannot be ruled out). The main room followed the

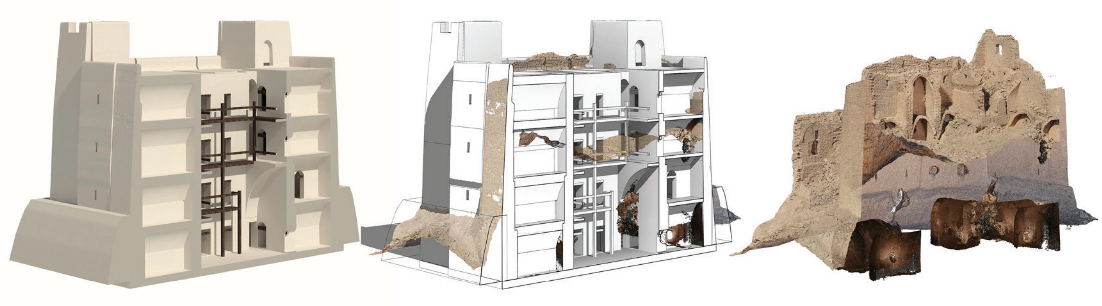
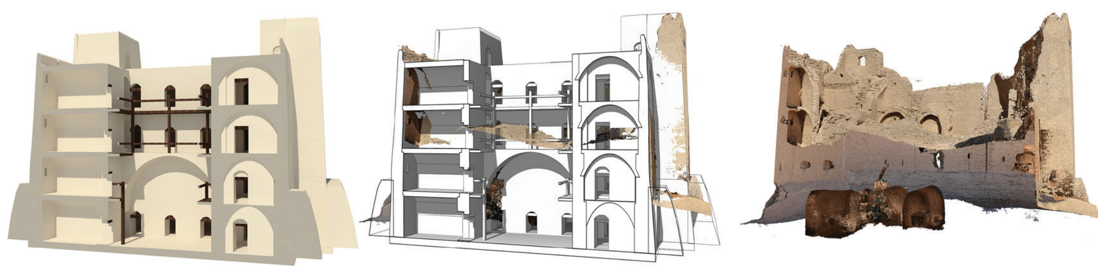


Fig. 4 - East-west perspective section of the one of the hypothetical reconstructions of the Fort (left), its overlap with the point cloud (centre) and the photogrammetric point cloud alone (right).

Fig. 5 - North-south perspective section of the one of the hypothetical reconstructions of the Fort (left), its overlap with the point cloud (centre) and the photogrammetric point cloud alone (right).



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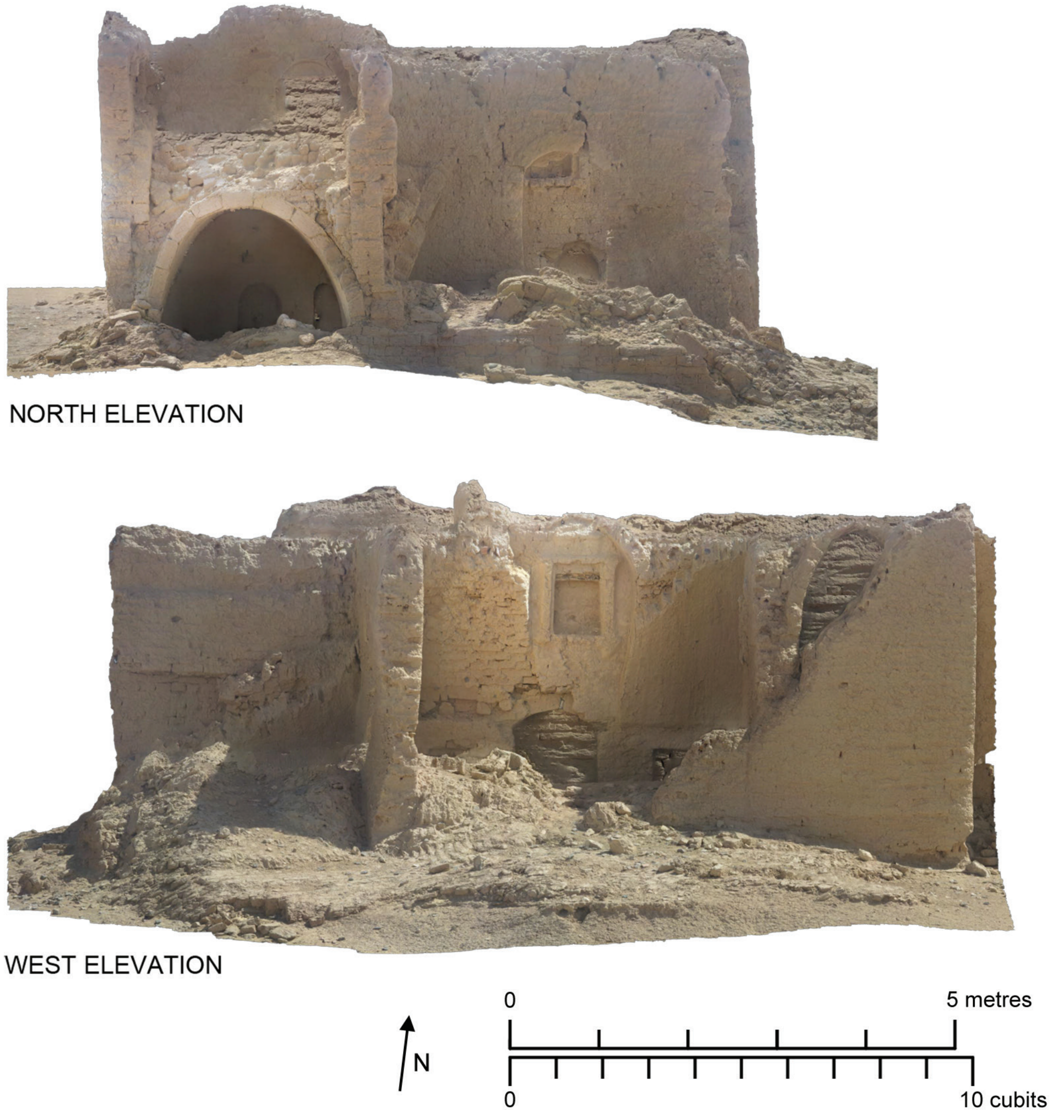

Fig. 6 - Orthoimages of the northern and western façades of Unit A.

typical design of the local domestic units and was covered by two barrel vaults with intersecting inclined brick courses; these are partially collapsed but can be still distinguished. Access to the house was from the south side through a room followed by a vaulted vestibule, above which there is probably an open space, presumably used as a kitchen. The vestibule connects to the room containing the staircase, which allows also access to the main room which, in turn, gives access to two rooms on the north side and one room in the southwest corner. The two northern rooms were probably used as bedrooms. The one on in the northwestern corner is a full-height room like the main hall, while the northeastern room has a lower height because above it there is another room of similar size, but covered by a very low vault; this, and its proximity to the open-air space that may be identified as the kitchen, suggest that this room might have been some sort of storage. The red arrows on the drawings of the ground and first floors (fig. 7) indicate the access to the different rooms.

Unit A is a well-preserved domestic building, and for this reason it was possible to elaborate a realistic geometric reconstruction. In order to model it, we first identified the different functional spaces that make up the structure, establishing their shape and dimensions. The remains allow an almost total reconstruction of the rooms on the ground floor and first floor. On the west and north sides, the walls collapsed and for this reason, there is less information regarding the exact outline and the presence of niches or openings on these sides. On the north side, some vaults also collapsed, and one is buried under the sand, but their traces on the walls and the metrological studies allowed to reconstruct their dimensions. In particular, orthoimages (fig. 6) floor plans (fig. 7), and sections (longitudinal and transversal) of the building in its current state and in its hypothetical original form were elaborated from the photogrammetric point cloud. On the floor plans the dotted line was used to indicate the layout of the hypothetical shape drawn on the archaeological traces.

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In order to reconstruct the shape and geometry of the missing parts, the metrological analysis offered a significant help. Figure 8 shows the ground and the first level of the house on which a 1-cubit grid has been superimposed; it is possible to note how the cubits grid provides a geometrical interpretation of many architectural elements. Indeed, apart from slight irregularities inherent in mudbrick construction, the layout of the building appears to be quite regular: the walls are 1 cubit thick, the niches 1 cubit wide, the main doors 2 cubit wide and the rooms generally follow a simple dimensional patter (for example, the stairwell is about 4 cubits and the living room is a square 7 x 7 cubits). The function of this grid is to highlight the presence of the unit of measurement in a visual way (cf. Rossi 2020: 230-3); it does not suggest that a grid was used to design or to construct the building (Rossi and Fiorillo, 2018: 378-82). In conclusion, these technical drawings also include the hypothetical parts (dotted line), that can be therefore used to extend the metrological analysis of the remains from the visible to the invisible portions of the building.

These technical drawings were fundamental and were used as a reference base to develop the 3D model of the domestic unit in Rhinoceros software, which is more suitable for the modelling of complex shapes. In fact, the typical living room of the local domestic units is covered by the same system of two intersecting barrel vaults, but of slightly different sizes. The 3D geometry modelling was developed by isolating every single room for which it was possible to reconstruct the slightly irregular shapes of walls and related barrel vaults. The vertical connecting element, the staircase that allowed access to the first floor, was reconstructed according to the inter-floor distance to be covered and the planimetric dimension of the stairwell. The shape and size of the profile of the latter

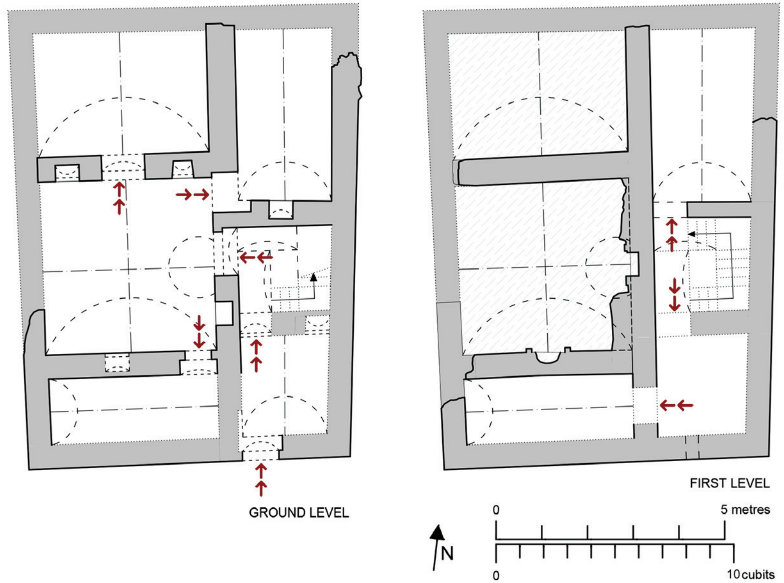

Fig. 7 - Floor plans of the current state of Unit A. The red arrows indicate the access to the different rooms.

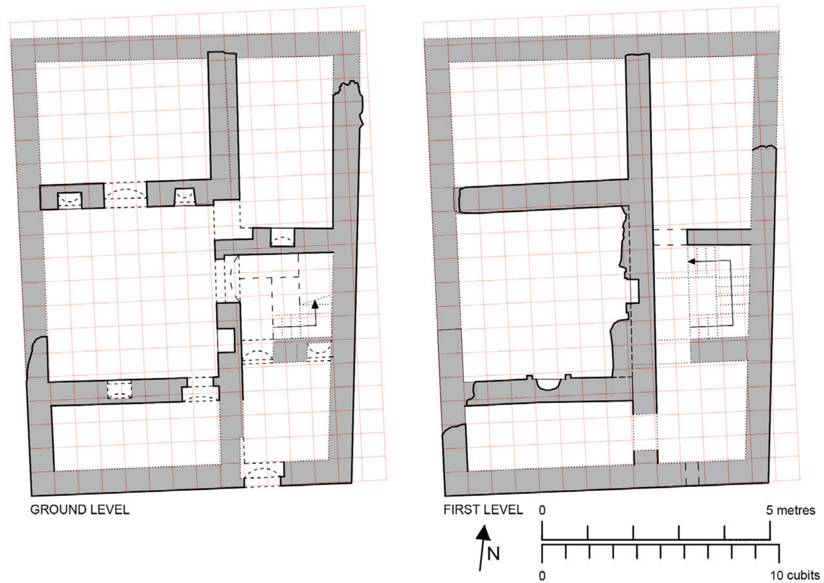

Fig. 8 - 1-cubit grid (52 cm), in red, superimposed on the floor plans of Unit A.

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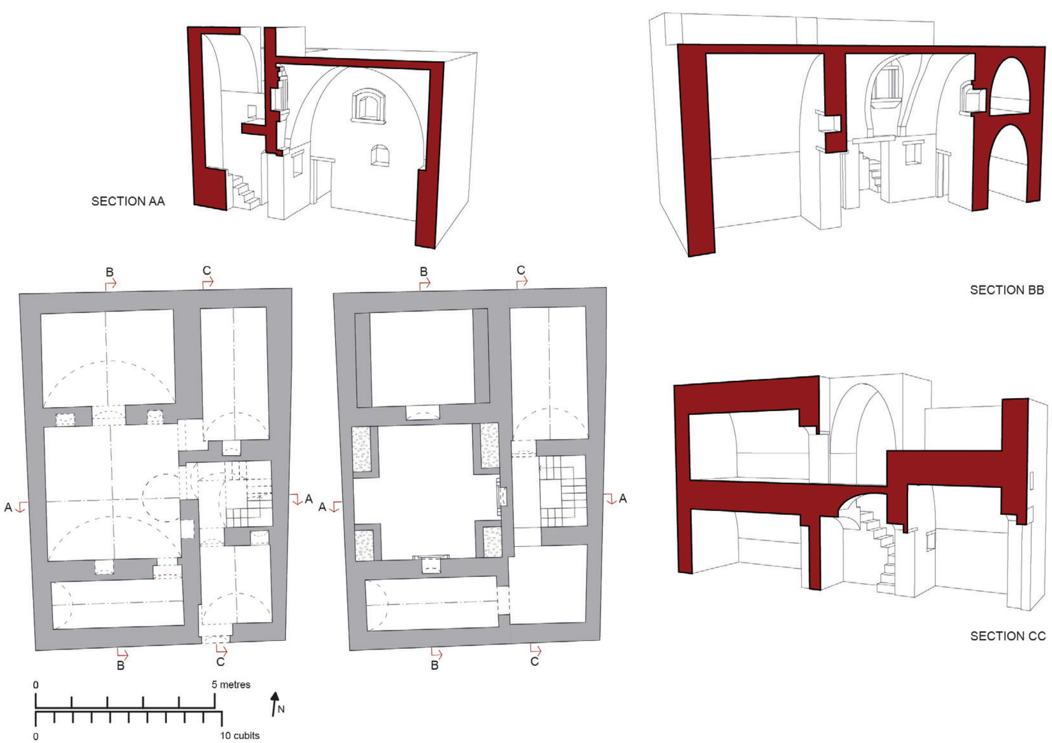

Fig. 9 - Hypothetical virtual reconstruction of Unit A: floor plans and perspective sections.

were obtained from the neighbouring rooms. In fact, despite the fact that there are neither photographic nor metric surveys of the stairwell, previous sketches and drawings by hand allowed us to understand its C-shape consisting of 3 flights and 3 landings. The first flight rests on a solid volume, whilst the other two on mudbrick rampant arches. The step number and the dimension size of rise and tread were calculated to equal to 20 x 20 cm and were compared with the size of some stone steps found in nearby houses. The treads are actually very small; this characteristic can be also noted in the other domestic units.
The shape and size of the niches have also been studied in detail. The identification of some specific geometric elements that appear repeatedly in their design will be useful to model partially visible or destroyed niches that are visible in other domestic units of the settlement. Unit A has been recomposed in its hypothetical original form (fig. 9) by modelling what could be measured, identifying modules and repeatable geometries and suggesting a reconstruction of the disappeared elements on the basis of the metrological studies. The walls were modelled as volumes, starting from their geometric shape in plan and extruding the profile up to the identified height. Inside them, the niches and the doors have been carved out from the solid volume.
The primary solid modelling operations used in Rhinoceros software were: the Boolean union to join the constructed solids (for example, the different walls); the Boolean difference to subtract a volume (to create, for example, openings or niches); the Boolean intersection to create new shapes (fig. 10-11).
The complex morphology of the biaxial vaulted system would have been difficult to model with a more rigid software such as Revit. Instead, in the Rhinoceros environment, it was possible to recreate the 3D model of the biaxial vault using tools to extrude profiles and subtract and/or add simpler shapes. The photogrammetric point model was imported into the software to adapt the modelling of the reconstructed volumes to accurate measurements (fig. 12).

6. CONCLUSIONS

Both approaches proved to be very effective. The study and development of the buildings in the three spatial dimensions help to comprehend their form and function, and are also able to suggest new possible interpretations.
From a practical, experimental point of view, Revit clearly allows a more efficient point cloud management for the direct modelling but presents instead more rigid modelling tools that are not suitable for complex architectural forms. Moreover, the Building Information Modelling data management falls out of scope of our current studies, whereas the flexible geometric modelling typical of Rhinoceros can yield more useful results.
It must be underlined that, in both cases, a first semantic analysis of all the architectural elements of which the buildings are composed was essential. The architectural decomposition and the individuation of all the modular and repeatable elements represented the first step to virtually recompose the structure of the archaeological remains. In this specific case, the semantic analysis of decomposition and re-composition of the architecture must be necessarily based on an interdisciplinary historical and archaeometric study (Ferdani et al, 2019) to identify the basic patterns, layout and architectural types.

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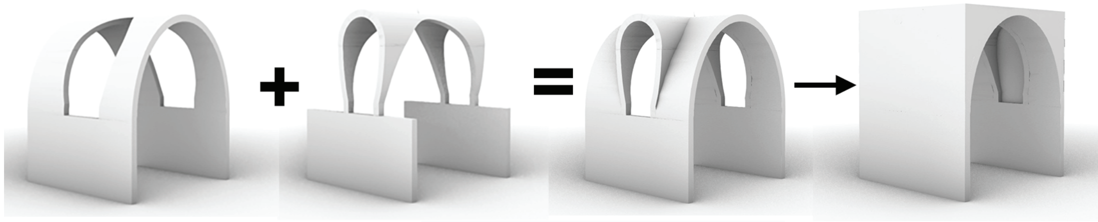

Fig. 11 - Partly elaborated shapes for the modelling process of the biaxial vaulted system of the living room of Unit A (Boolean union).

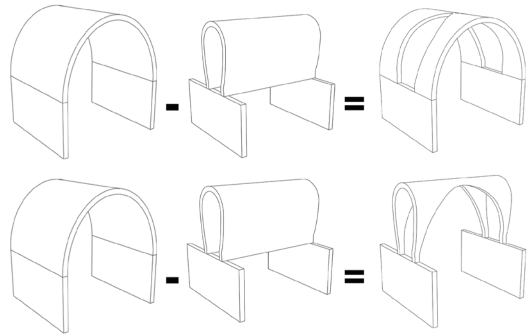

Fig. 10 - Primitive forms for the modelling process of the biaxial barrel vault of the Unit A (Boolean difference).

Fig. 12 - Overlap of the actual point cloud of Unit A with its reconstructed model (north-south perspective section).

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