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3D Parametric Modelling based on Point Cloud for the Interpretation of the Archaeological Remains

In the archaeological realm, 3D survey has been gaining importance because it allows to accurately capture the relationship between the objects and their contexts, which is inevitably destroyed during an excavation. The ensuing 3D modelling allows a morphological/geometric analysis and an interpretation/classification of the architectonic proprieties (features typologies and styles). An interesting application is adopting parametric modelling to study the modular features and repetitive architectural elements and to define an interpretative geometrical model. This approach implies: (i) the identification of similar and recurring architectural features and (ii) their semantic classification, (iii) their modelling and fitting on the survey data and (iv) the parametric reconstruction of comparable missing parts. This approach appears to be particularly useful in the study of archaeological remains characterized by a modular construction technology, including both basic elements (such as bricks) and architectural elements (such as barrel vaults), as is the case of the late Roman Egyptian settlement that is the object of this study. All buildings are constructed of mudbricks and consist of different compositions of rooms covered by pitched-brick barrel vaults, and the mudbrick building technique suggests the use of modular measurements of walls, vaults and rooms. The reality-based parametric modelling may support the process of interpretation of the surveyed remains and of the reconstruction of those that are invisible, because hidden under the sand, or because no longer existing.

Keywords:
close-range photogrammetry; architectural classification; metrology; geometry reconstruction; Late Roman forts

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1. INTRODUCTION AND BACKGROUND

In the archaeological realm, the 3D survey has been gaining importance for two main reasons: it is able to accurately capture the metric data and, at the same time, realistically records the relationship between objects and contexts that is inevitably destroyed during an excavation (Greco, 2019 and Rossi, 2019a). Moreover, the ensuing 3D modelling allows a morphological/geometric analysis and an interpretation/classification of architectonic proprieties (features typologies and styles) (Russo et al, 2019).
Parametric modelling, typical of a BIM-oriented approach, also becomes part of the cognitive process in the archaeological realm (Diara and Rinaudo, 2020). This approach is often used to model small objects, such as vessels (Varinlioglu et al, 2014), but is also developing into new, more specific branches of activities. The so-called archeoBIM (as defined in Garagnani, 2017), for instance, can also be used as a representation tool to attach different types of information to an object; it may also act as a shared platform (Croce et al., 2020) for the exchange of information between academic and technical users for an architectural or archaeological analysis of existing heritage (Trizio et al. 2019).
In general, the concept of "Historic Building Information Modelling (HBIM) is proposed as a new system of modelling historic structures; the HBIM process begins with remote collection of survey data using a terrestrial laser scanner combined with digital cameras." (Murphy, 2009). The HBIM approach for the field of Cultural Heritage is a current and interesting topic for the area of graphic representation that expert researchers are exploring with many different aims and perspectives. The integration of 3D modelling and information system is the BIM core characteristic. The optimization of the 'scan to BIM' pipeline (Bologensi and Caffi 2019; Tommasi et al., 2016) and the opportunity to create parametric libraries for historical building construction elements (Brusaporci et al. 2019) are some of the many topics of ongoing discussion.
The HBIM method it is efficiently used to include data relating to history, restoration or maintenance in a single digital environment, and to ensure that the documentation on the building conditions is regularly and constantly updated over the time (Di Luggo and Scandurra, 2014). Moreover, it is also used to speed up and automate the geometric interpretation and modelling of complex and irregular shapes, typical of the historical building (Bagnolo et al., 2019 and Barazzetti, 2016).
In the HBIM applications, most of the problems arise because BIM software is designed for new construction (regular and simple geometry) rather than the management of the existing heritage; however, it can still be beneficial to plan maintenance interventions and to monitor activities (Contineza et al., 2016).
A specific, interesting application is the adoption of parametric modelling to study the modular features and repetitive architectural elements and to define an interpretative geometrical model. This approach implies (i) the identification of similar and recurring architectural features and (ii) their semantic classification (iii) their modelling and fitting on the survey data (iv) the parametrically reconstruction of comparable missing parts. This approach appears to be particularly useful in the study of archaeological remains characterized by some sort of modular construction technology,

Fig. 1 - The Late Roman settlement of Umm al-Dabadib (Kharga Oasis, Egypt).
Fig. 2 - Photos of the same domestic unit, taken in 1999 (left), and in 2014 (right) showing the typical pitched-brick barrel vaults.

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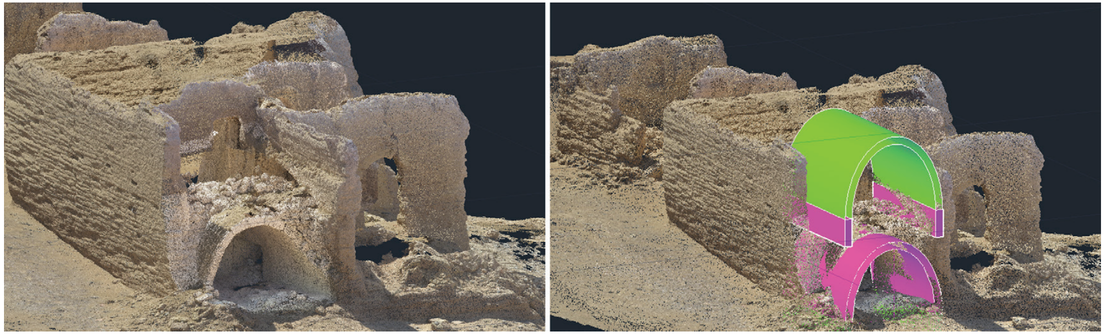

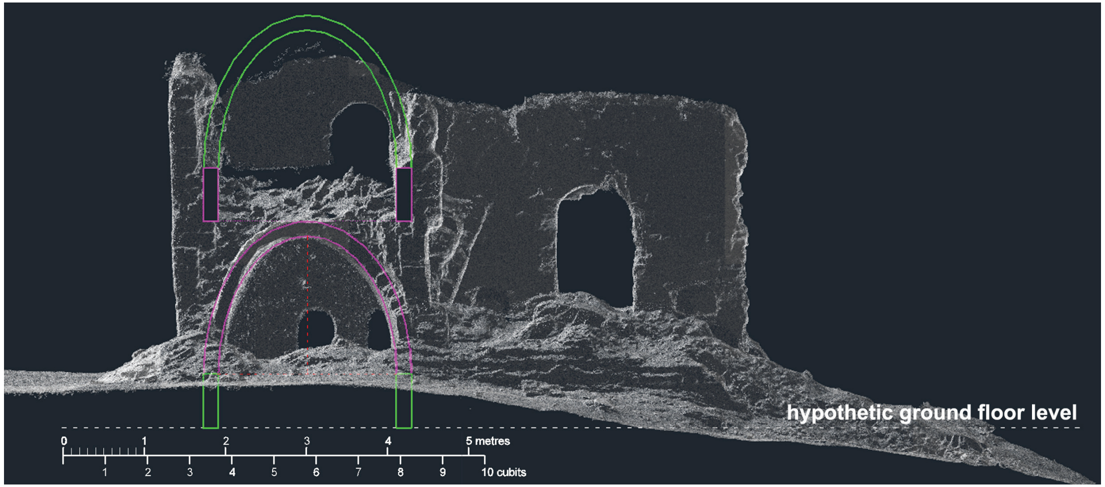

Fig. 3 - The point cloud to the left, and the geometrical reconstruction of the vaulted room to the right. Magenta is used for the shape interpolated from the point cloud; green for the hypothesis of modular reconstruction.
Fig. 4 - The green modular shapes can be used to suggest the position of the ground floor and the maximum elevation of the roof.

including both basic elements (such as bricks) and architectural elements (such as barrel vaults), as it is the case of the late Roman Egyptian settlement that is the object of this study.
In this research, parametric modelling was used not to represent the detailed geometric/radiometric information of the existing remains but to work on the virtual reconstruction of the building, based on the measurements and the available historical documentation. As we shall see, the approach based on the possibility to combine repetitive architectural elements strictly adhering to and modelled on the archaeological remains allows to explore in detail the potential of immaterial reconstructions: differently from the material reconstruction of an ancient building, that can only be one and cannot be easily modified in case fresh evidence comes to light, immaterial reconstructions can be more than one, are not mutually exclusive, and do not affect the perception of the building in a permanent way. Moreover, being less 'fixed', they better respect the evolution of our own interpretation of the ancient remains, that is constantly modified by the addition of fresh evidence (Rossi, 2019b).

2. CASE-STUDY

This paper discusses the typologies classification, the geometrical interpretation and 3D parametric modelling of the archaeological and architectural remains of the Late Roman settlement of Umm al-Dabadib (Kharga Oasis, Egypt) (fig. 1). A well-preserved fort occupies the centre of a compact settlement, in which several domestic units (fig. 2) can be clearly identified; an early Christian church was added at some point along the eastern side. This site was part of a network of forts and settlements stationed in the Oasis to control the caravan routes and the borders of the Roman Empire (Rossi, 2018). All buildings are constructed of mudbricks and consist of different compositions of rooms covered by pitched-brick barrel vaults (Lancaster, 2012).
This architectural element is also known by the name of Nubian vault (Zabrana, 2018) and it is the most common vaulting method found in the region. Its essential characteristic is that it can be built without any temporary support during construction, thanks to a succession of oblique arches that rest on the back wall of the room to be covered (Van Beek, 1987).
This technique has been used as early as the third millennium B.C. in Egypt and Mesopotamia. Over the centuries, it spread to all arid and semi-arid areas where wood was scarce. In technical terms, these barrel vaults are formed by a succession of oblique arches (self-supporting courses) made of mud bricks arranged edge-to-edge (Wendland, 2007). They were built with the aid of gypsum mortar, which stabilises much faster than lime mortar, thus ruling out completely the need for wooden formwork (Lancaster, 2009). The triangular spaces between the vault extrados and the vertical walls were filled with debris containing small, round, white stones and then covered with mortar to create the walking surface.

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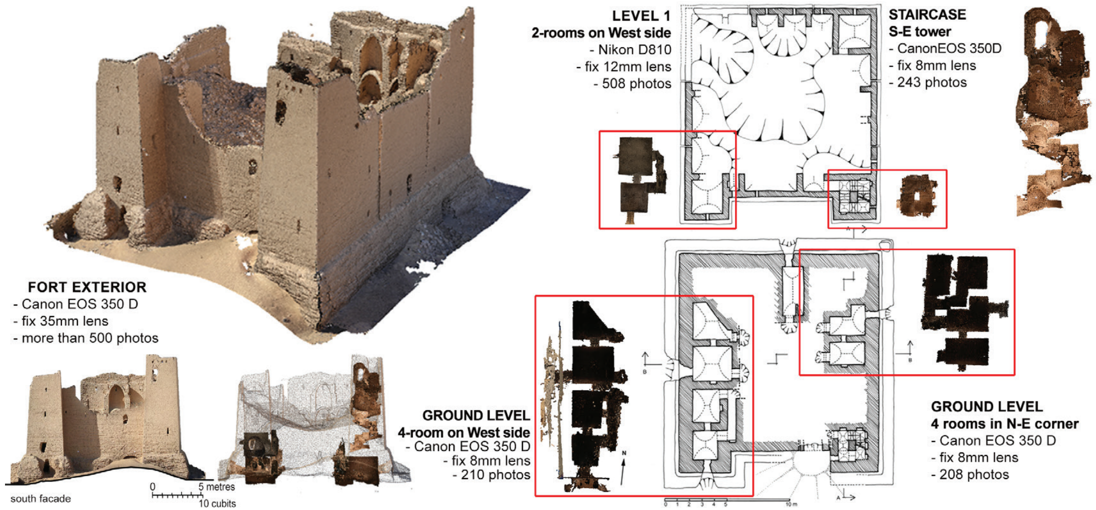

Fig. 5 - The photogrammetric survey of the exterior and the interior of the fort. To the right, the direct survey (Rossi, 2018).

Thanks to the digital survey and the excellent preservation of the building, it was possible to analyse the geometric form of the vaults in connection with the ancient construction techniques (Rossi and Fiorillo, 2020). The mudbrick building technique suggests the use of modular measurements of walls, vaults and rooms; in particular, the metrological analysis on the fort showed that the building was planned and built according to the Egyptian Reformed Cubit (Rossi and Fiorillo, 2018). In these conditions, a parametric 3D model based on the photogrammetric point cloud can indeed help to understand and reconstruct the missing metric information. It may also support the process of interpretation of the remains that were surveyed and of the reconstruction of those that are invisible, either because hidden under the sand, or because no longer existing.
The final 2D outputs are still fundamental products to perform a historical analysis and geometrical comparisons with previous interpretations of the layout of this and of similar settlements. However, a 3D georeferenced model of the geometry of the main building, based on the point cloud, can help to understand and hypothesize shape and dimension of the invisible parts (fig. 3).
This method can be especially useful to analyse the vertical sections, where the lack of metric data is more evident. For example, due to the presence of blown sand, the level of the floor at ground level is hidden in the vast majority of cases; this, in turn, prevents us from establishing whether there was a common ground floor for the entire settlement, or whether each building had its local ground reference (fig. 4).
The entire site of the Fortified Settlement, covering an area of about one hectare, was surveyed using a close-range terrestrial photogrammetry approach in 2014 and 2015 (Fassi et al., 2015). The first case-study used to test the BIM cognitive approach to interpret the archaeological remains of the settlement was the fort. This building has an almost square layout and is completed with two rectangular towers; the interior consists of sequences of narrow barrel-vaulted rooms arranged along five levels. The external surface of the fort was acquired in 2014 thanks to more than 500 photos using a Canon EOS 5D Mark III and a 35 mm lens (fig. 5), whilst the inner, narrow spaces were surveyed in 2015 with fisheye lenses.
In particular, a Canon EOS 350D coupled with an 8mm lens, was used for the ground floor and staircase; four rooms on the east side and four rooms in the northeast corner were accessible, and fully 3D measured on the ground floor; two more rooms on the east side of the second floor were surveyed with a Nikon D810 and 12mm focal length (Fiorillo and Rossi, 2017)

3. WORKFLOW

The photogrammetry-to-HBIM workflow can be summarised in the main following steps: i) acquisition and processing of survey data; ii) optimisation of the point cloud model (cleaning and decimation with fixed point-to-point step); iii) creation of the RCP project to import directly into REVIT environment; iv) architectural components classification and BIM modelling.
The management of the point cloud within the work environment allows to recognise each of its points as a snap, and it is therefore possible to take direct measurements on the model. Moreover, within the BIM software it is possible to generate plans, sections and elevations of the building, which further facilitate understanding, interpretation and finally modelling.
Before starting the actual modelling phase, a semantic segmentation is necessary to disassemble architectural structure into simpler elements according to their constructive and structural components (fig. 6). Therefore, BIM applied to the historical buildings needs an initial step of meta-modelling that consists of the architecture decomposition (Bianchini and Potestà, 2020). The elements of the model must be classified and distinguished in two macro-categories: replicable and non-replicable. For this case study, loadable families [1] were used

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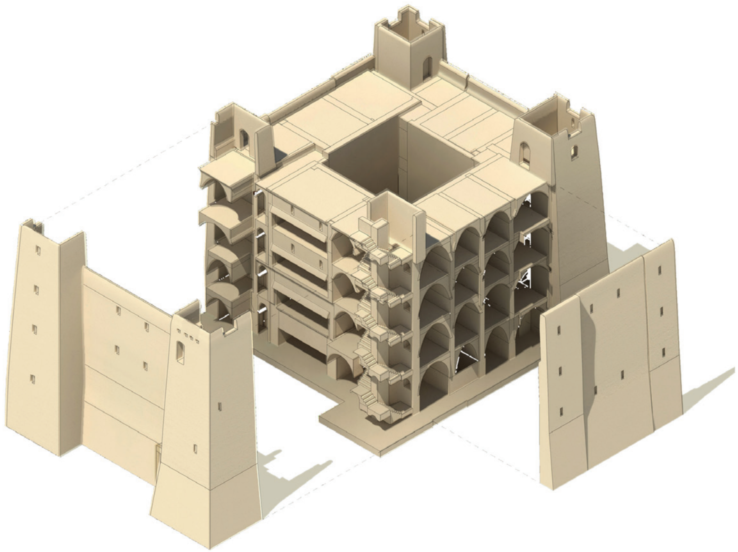

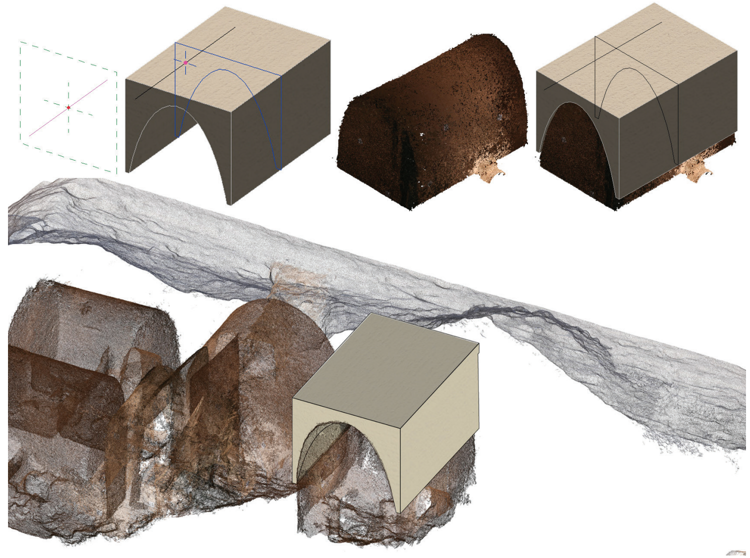

Fig. 6 - Architectural decomposition of the reconstruction of the fort.

Fig. 7 - Barrel vault modelling (in-place family) based on point cloud.

to create beams and columns that define a hypothetical wooden structure to access the upper levels (see below). Most of the architectural components of the fort are instead constructed as in-place families [2], thanks to less constraining modelling tools, such as the extrusions tools (fig. 7). The profile to be extruded was created directly by drawing the section from the point cloud.
The in-place family was based on the unit of measurement of the fort, the reformed Egyptian cubit. The mud bricks used for the entire settlement have average dimensions of 34-36 cm x 16-18 x 8-10 cm. The masonry layout of the interior partitions corresponds to three heads, for a total thickness of approximately 52-53 cm. The outer wall gets thinner as the height increases: five heads at the basis are only two heads thick at the top floor. This metric information was tested on various portions of the building by direct visual inspection, consulting photos, and measuring the digital model. This metric module of 52-53 cm corresponds precisely to the unit of the reformed Egyptian cubit (Rossi and Fiorillo, 2018). Besides, the height of each plane (vertical distance between the apex of the extrados of two vaults) measures exactly 5 cubits.
A modular grid of 52 cm was superimposed to the point cloud as a reference base to check the floor-plan layout and the wall thickness during the modelling phase (fig. 8).
This approach has been advantageous to interpret the survey data (not always easy to read), and to define type and thickness of the walls according to the corresponding level. Moreover, a modular measure also facilitated the generation of the reconstructed parts, using precisely repetitive elements and drawing them through the basic module of 52-53 cm.
The first operative step of the BIM modelling is defining levels and reference grids through which the building can be constructed in the virtual environment. All the construction components will refer to these references, identifying the planimetric and altimetric position of the architectural elements in the space.
The metrological studies of the fort allowed to establish that the inter-floor distance between the levels is 2,6 m (5 cubits). This information allowed to identify and then arrange more easily the floor levels even in the areas of the building for which there were no data. After this preliminary step, it was possible to move to modelling the various building components (walls, roofs, floors) and then, once the architectural envelope was defined, the openings (doors and windows) and the vertical connections (stairs) and so on until completion. All openings were modelled as volumes subtracted from the masonry.
The exterior perimeter walls have different inclinations depending on the side. Therefore, the wall system family could not interpret such an irregular shape. Perimeter walls and basement were modelled using in-place families and identifying significant reference sections to develop the extrusion along the vertical axis (representing the extrusion path). Section profiles were drawn from the point cloud.

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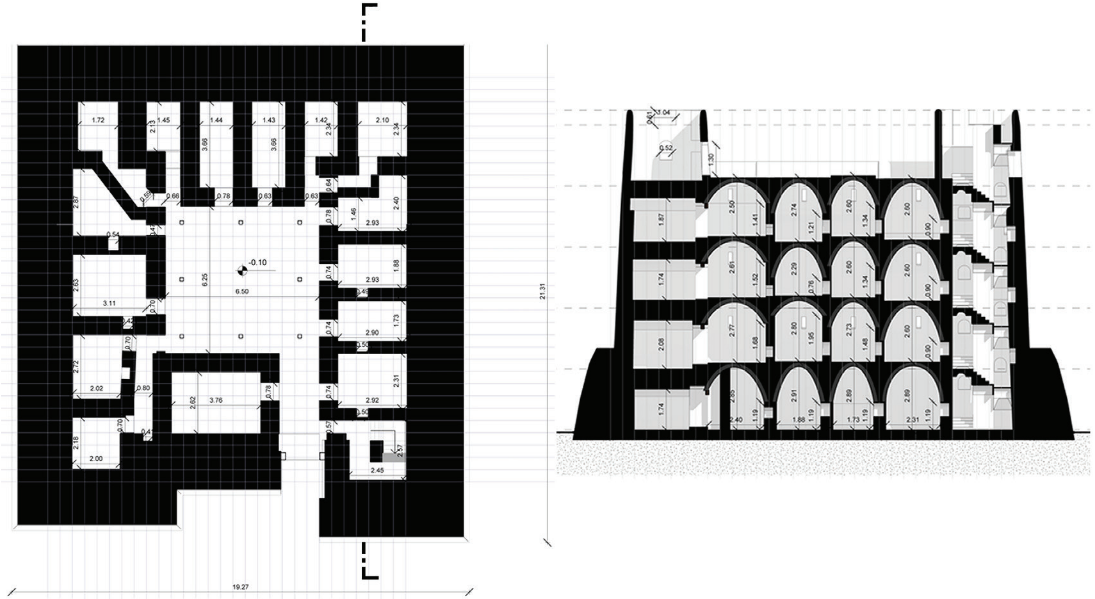

Fig. 8 - Ground level floor plan and N-S section (on the staircase) looking east of the reconstructed fort. A modular grid of 52 cm (reformed Egyptian cubit) was superimposed.

The barrel vaults were also modelled, creating floors as an in-place family and then modified according to the specific geometry. It was not necessary to use the mass modelling. The vault transversal profile was defined, and the shape was extruded from it along the path represented by the longitudinal axis of the vaulted room. In this way, the vault intrados and the floorplan were defined, to which a thickness of 18 cm was associated.
The digital survey allowed to define the profile of 13 barrel vaults, of which 10 entirely and integrally visible and measured in 3D, and 3 partially visible. The barrel vaults have been individually modelled according to the survey data. The metrological study on the fort has also highlighted that the layout of the vaulting system repeats itself along the vertical axis, presenting similar geometrical characteristics. Therefore, once defined the vault model at the floor level, its shape/geometry has been repeated and adapted to the upper floors in the missing areas, according to the visible evidence.
Finally, the staircase was modelled. The latter was created as local models with four different extrusions to include both vaults and steps, according to the point cloud.
In Table 1 are summarized the types of families (fig. 9) used to create solid geometries, constituting the virtual correspondents of all the architectural and structural building parts: walls, floors, vaults, stairs etc.
Finally, the construction material (clay) was assigned to the model, and abacuses were made for the generated elements. The abacus allows to keep under control the number of families used and its topology (in our case, all in-place families, except for beams and pillars of the wooden structure, see below). The very last step was to orient/geo-localize the model to contextualise it in its territory. This step allows, in the rendering phase, to generate the shadows with greater authenticity and enrich the information on the territorial context.
Several conclusions may be drawn from this experience: first of all, it is evident that the libraries of parametric objects, which are explicit within BIM programs, poorly adapt to the plurality of materials and construction techniques typical of archaeological contexts; then, the recognition and three-dimensional modelling of shapes for the generation of local model adhering to the point cloud are not automatic. Moreover, the support of bi-dimensional technical drawings or even simple linear measurements on the cloud is fundamental, in this first phase, to define the volume geometry; the representation proved to be quite complex, requiring an initial simplification in plain geometric figures and a reduction of the geometrical details. The typical BIM logic of efficiency inspired a more useful compromise in the phase of modelling (Brusaporci et al. 2020), thanks to the creation of less detailed elements - but strictly connected on the point cloud geometry - which could be 'reusable' for the areas to be reconstructed.
In conclusion, the generated HBIM model does not totally adhere to the actual state of the fort. This model cannot replace the point cloud model or the polygonal model generated by the 3D survey. However, it may represent an extremely useful tool to understand the original architectural shape, structure, and layout of the building.

4. RECONSTRUCTION HYPOTHESES

The BIM modelling approach was thus used to test the possible reconstruction(s) of the fort. Several hypotheses can be made on the basis of the available set of 3D survey and historical data.
This operation generated a virtuous circle: modelling some parts allowed to suggest a function for features that had not been explained before. This is the case, for instance, of the north-eastern and north-western corners of the building, which might have been completed by taller walls replicating the upper portions of the two towers that flanked the southern façade. It is even possible to

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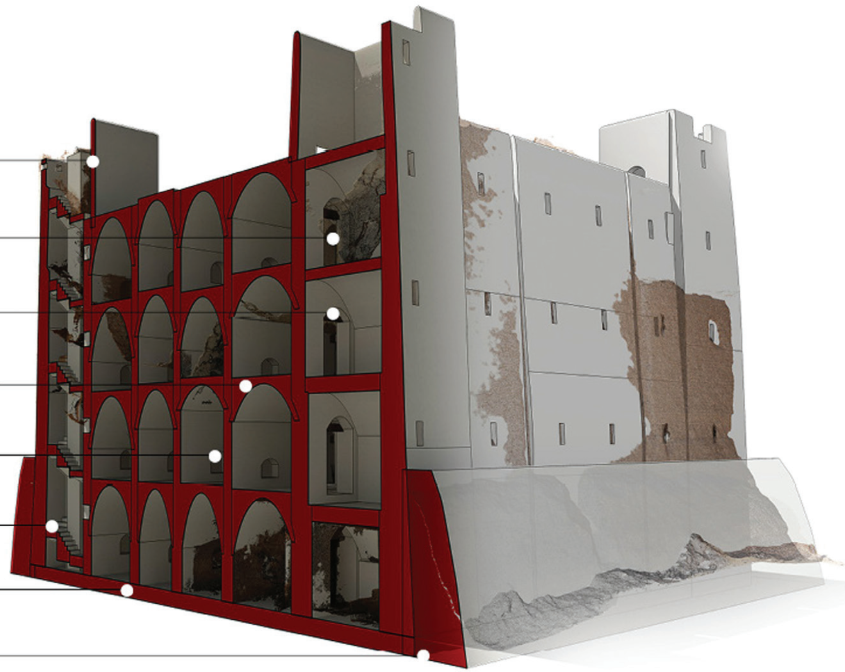

Fig. 9 - Types of families used to create solid geometries of the fort - section view of the N-E corner (graphic elaboration by Chiara Mea).

suggest that the four protruding parts were endowed with crenellations, 2 cubits wide and 1 cubit tall. Figure 10 shows the geometry reconstruction of the structure, where is evident in the line of the modelled architectural features.
Many important details about the building internal distribution remain uncertain, including the exact dimensions of the inner court. The layout of ground floor and first level is relatively clear and detailed, as the ground floor can be reconstructed partly from the accessible remains and partly by projecting the alignment of the upstairs rooms. The second level is submerged by sand and debris, and remains unexplored. The remains of the third and fourth levels can be seen today emerging from the collapsed mass of debris in the courtyard of the fort. Once the profile and design type of the visible vaults was identified, it was extended to partial profiles emerging from the ruins; this helped to reconstruct the layout of the rooms and their shape, even if inaccessible and collapsed.
In all 3D reconstruction, the distribution of the rooms on different floors is likely to remain

Tab. 1 - The types of families used to create solid geometries, constituting the virtual correspondents of all the architectural and structural building parts: walls, floors, vaults, stairs etc.

System families	Grid and Levels	The only system families used are grids and levels. These are standard components predefined into the software that can be duplicated to assign specific characteristics but not create, modify or delete. The result is the variation of established parameter values without graphical editing.
Loadable families	Beams and pillars	This family type is a customisable template includes in a software library. The family editor allows defining the measures suitable to the modelled geometry. This modelling solution is valuable and ideal in determining the fort original reconstruction of the missing part working with more regular geometries.
In-place families	Brick walls, barrel vaults and openings	These are custom elements generated within the specific project. Vaults and masonry are too specific and cannot be placed in other projects or cloned within the same project. The elements can also be categorized. The strength is that one can model according to the survey measurements and the unit of measurement (here the Reformed Cubit).

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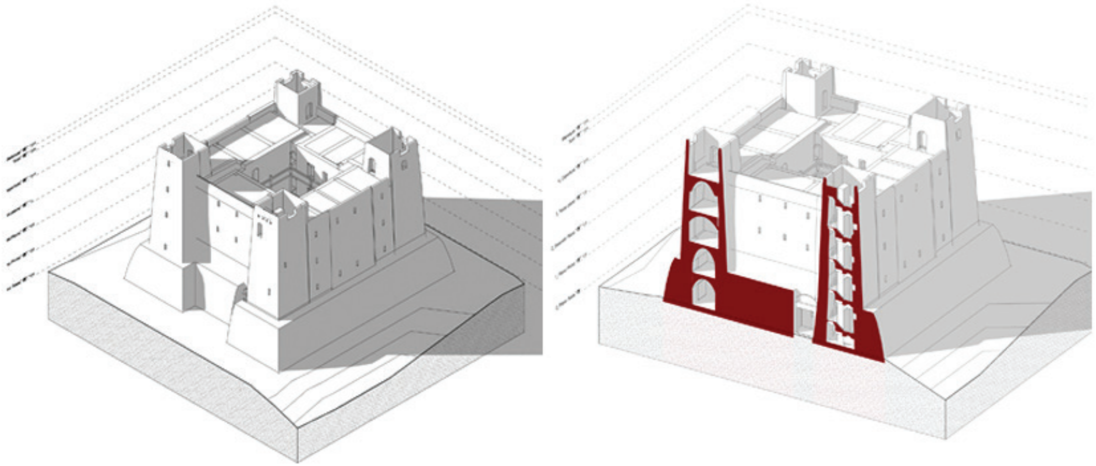


Fig. 10 - Final reconstruction of the fort (graphic elaboration by Chiara Mea).

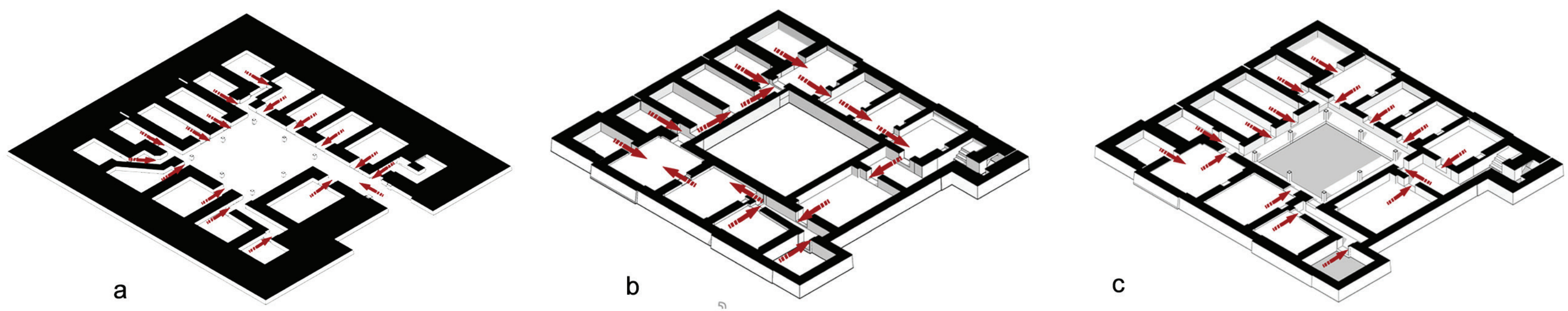
practically the same. However, the circulation on each level is still unclear, and several possible solutions have been taken into account. The rooms in the northwest and northeast corners were accessed respectively from a diagonal corridor and a right-angled corridor, obtained by dividing the barrel-vaulted rooms with a thin wall (fig. 11). The southwest corner was reached by a narrow corridor parallel to the outer wall. The rooms on the ground floor probably had access from the courtyard, but another system must necessarily have been employed for the rooms on the upper floors. There may have been open passages excavated by reducing the width of the rooms as at Qasr al Gib, but in practice, the adoption of this system in a taller building would excessively reduce the extent of the upper rooms. The most plausible explanation is that there was a passageway within the court, probably made of lightweight materials, as may have been the case at Qasr al Lebekha (Rossi 2018, 434-44). Only future archaeological excavations and analysis could clarify this point.

In the simplest reconstruction, the circulation on the various floors could have been achieved thanks to a wooden structure that ran along the faces of the inner walls overlooking the central courtyard (fig. 12). All the small vaulted rooms, therefore, were accessed from it, similarly to the ground floor.

The point cloud, however, registered the presence of a vault or arch intrados in the north-western corner of the internal courtyard, which was noted in 2014 and documented with some difficulties. The geometrical analysis demonstrates that its intrados surpassed the first level, reaching its maximum height precisely at the second level.

In a second reconstruction (fig. 13), thus, we suggested the presence of an arch spanning between the northern and the southern internal façade and running along the eastern façade, that supported a suspended passage providing access to the rooms of the second level. This type of configuration would also allow to avoid the presence of a pillar in front of the main entrance (fig. 14). The elaboration of the second hypothesis suggested a third possibility, that is, the

Fig. 11 - Circulation patterns: a) ground level from the courtyard; b) internal for the upper floors; c) external for the upper floors (graphic elaboration by Chiara Mea).



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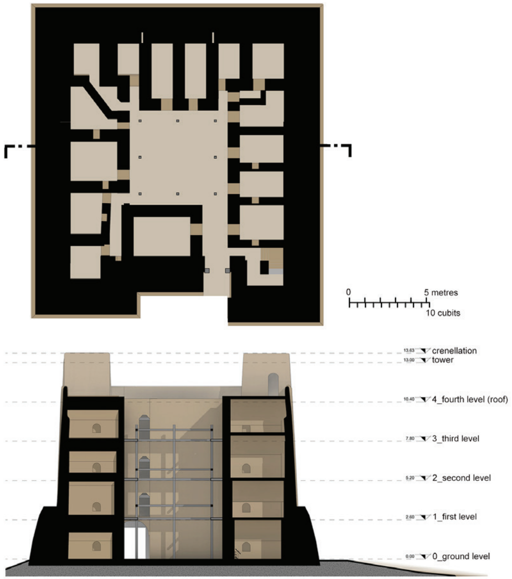

Fig. 12 - Ground level and E-W section looking south of the first reconstruction. The circulation on the various floors could have been achieved thanks to a wooden structure along the inner wall in the central courtyard.

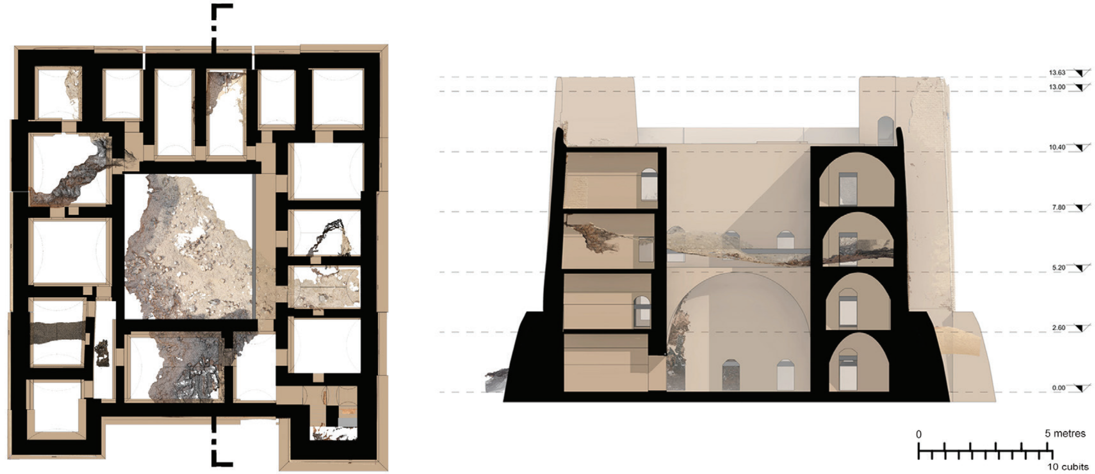

Fig. 13 - First level and N-S section looking east of the second reconstruction. The point cloud is overlaid, it is possible to see the arc section of the point model used to interpolate the reconstructed arc profile.

presence of a symmetrical arch along the western side of the courtyard (fig. 15). As can be seen from the plan of the second level, the two passages that are consequently created ideally prolong the corridors that reached the corner rooms. In this way, only on the second floor, the room circulation would be divided between the outside and the inside in equal measure. On the east and west sides externally, on the north and south sides internally to the rooms.

In both cases, passing from room to room might have been the solution chosen for the first level, and perhaps the third as well. Other hypotheses are possible on the basis of slightly different interpretations of the same survey data. They will be the subject of further studies, including not only a careful geometrical analysis, but also the comparison with other buildings belonging to the same historical period and playing a similar function.

5. CONCLUSIONS AND FUTURE AIMS

The aim of this specific research is the definition of a workflow leading from the point cloud to a 3D parametric modelling of archaeological remains. Although born and optimised to model new buildings with regular and repetitive geometries, the BIM approach has been here satisfactory used for the virtual reconstruction(s) of the original layout of the fort of Umm al-Dabadib, that presents standard and repeatable shapes. Less effective and not viable was the modelling of the actual state of the same building, as erosion, collapses, irregular holes, cracks in the masonry, etc. are difficult to represent, but this is irrelevant as all this information is satisfactorily represented by the photogrammetric survey.

In general, a future research topic to address may be the application of a machine learning approach to the 3D point cloud automatic classification and segmentation (Teruggi et al., 2020), in order to optimize the workflow. Concerning the workflow illustrated on this occasion, it will be then interesting to extend this discussion to the remains of the entire settlement, also composed by sequences of vaulted rooms.

From a historical and archaeological point of view, the 3D parametric modelling may prove especially useful in the study of the Late Roman installations along the desert frontier, as Umm al-Dabadib. In these constructions converged several modules and standards, due to the combination of well-established local construction techniques with the recognizable patterns of Roman military strategy and propaganda. Being able to virtually deconstruct the Late Roman buildings erected along the desert frontier into an array of basic components can help to draw and recognize parallels and differences. In this respect, well-preserved sites such as Umm al-Dabadib can help the interpretation of less fortunate sites, that only survive in a fragmentary state.

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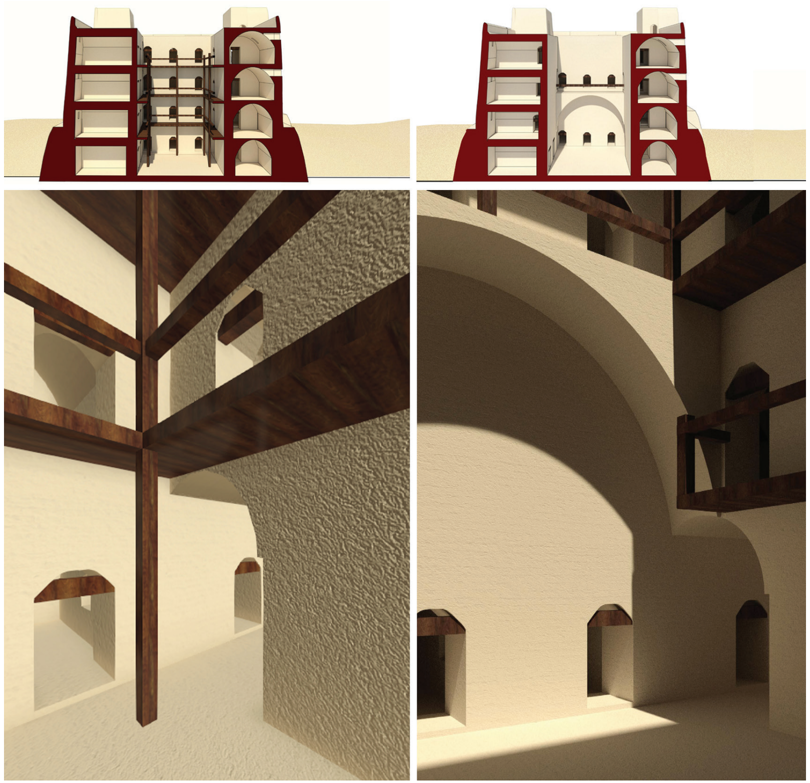

Fig. 14 - Perspective view form the centre of the court looking towards the main entrance of the two solutions. The second configuration (on the right) would also allow avoiding the insertion of a pillar in front of the main entrance (graphic elaboration by Chiara Mea).

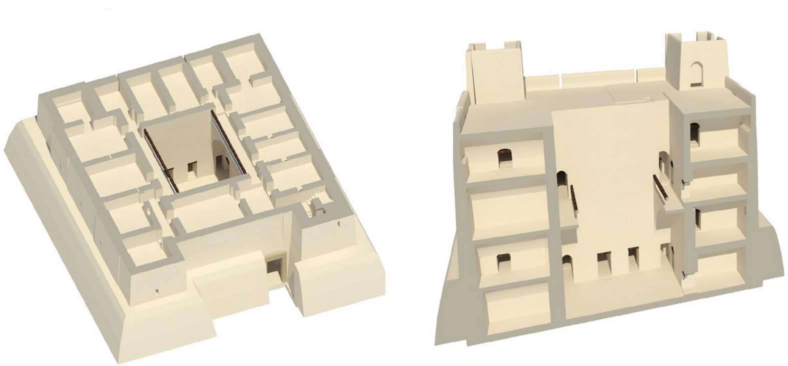

Fig. 15 - Second level floor plan of the third hypothesis with two specular arches (on the left) and N-S perspective section (graphic elaboration by Chiara Mea).

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NOTE

[1] All of the elements modelled into Revit projects are created with families (groups of elements with common parameters). There are three kinds of families: system families, loadable families, and in-place families. System families are predefined elements. Loadable families are created in external RFA files and loaded in the project.

[2] In-place elements are unique elements that are specific to the current project.

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