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Original article

HBIM for conservation and valorization of structural heritage: The Stylite Tower at Umm ar-Rasas, Jordan

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ABSTRACT

The Heritage Building Information Modeling (HBIM) is a consistent approach to support the multidisciplinary process of knowledge, conservation, and valorization of the historical building heritage, exploiting the combination of advanced 3D modelling and heterogeneous informative data. In the present paper, a highly customized HBIM workflow is developed for the enhancement and conservation of the byzantine Stylite Tower in the Jordan archaeological site of Umm ar-Rasas. The case study is considered a benchmark to test the effectiveness and the scalability of the proposed methodology for the broader set of ancient structures located in archaeological sites. The proposed HBIM process has a dual aim: the organization of heterogeneous and fragmented sources concerning the history and the actual state maintenance of the Tower and the development of a flexible tool to perform fast qualitative and quantitative analysis oriented towards conservation and management projects. The small scale of the structure and an innovative semi-automatic modelling process based on visual coding allowed for a stone-by-stone segmentation of the Tower. The model procedure is based on an information management workflow based on CIDOC-CRM ontology and the interchange format Industry Foundation Classes to ensure interoperability, developing an open-access interactive visualization of the model of the Tower, embedding organized document sources. The proposed HBIM model can also be a valuable tool for enhanced monument fruition and dissemination activities of the structure.

1. Introduction

The historical building heritage represents not only an inheritance of the past identifying the history of a territory but also a common fundamental value to be protected and preserved for future generations. The ancient building heritage is mainly characterized by structures with complex and irregular morphology and geometry, which have often undergone deep transformations over a century's time scale. Thus, the preservation and safeguarding of historical structures is a complex and challenging task involving different actors. In recent years, the sudden technological development in the survey, restitution, and virtual repository tools has allowed the ascent of Historic Building Information Modelling (HBIM), revolutionizing the entire panorama of the management of the built heritage [1–3] and Open HBIM approaches [4].

Among the main objectives of the HBIM processes for the structural heritage are the documentation of the structures, supporting the ongoing monitoring and maintenance actions and offering a multidisciplinary field of research and collaboration for historians, archaeologists, architects, engineers and managers [5]. In particular, the HBIM processes envisage the possibility of obtaining, at the same time, a 3D parametric representation of the physical object and a database where heterogeneous sources can be structured, taking into account the different elements of history and conservation state of the structure, and their mutual relations [6,7]. Thus, the HBIM modelling can be successfully employed for the management and conservation of historical buildings, showing great potential for the refurbishment process of the structures. In [8], the HBIM modelling is reviewed with particular attention to the critical aspects of diagnosis and performance assessment, proposing a new methodology for managing assessed performances and risks.

As introduced by Castellano-Román and Pinto-Puerto [9], three distinct HBIM approaches differing in methodologies, processes, scopes, and results can be identified. The first approach involves

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the HBIM of monuments or historic buildings with complex geometries via parametric modelling. A typical application addressed the virtual reconstructions of monuments that no longer exist [10–12]. A second approach aims to create HBIM with high geometric detail, exploiting the so-called scan-to-BIM procedures through manual or semi-automatic processing of point clouds based on photogrammetric and 3D scan surveys [13–15]. Lastly, the third approach is focused on the production of organized knowledge frameworks derived from document analysis of the construction process and on-site investigations, exploiting the traditional methodology of the architectural survey [9,16,17].

The present work addresses the specific subset of structures in the archaeological sites that are usually featured by unique cultural values, complex geometries, partial integrity, and heterogeneous document sources, representing a significant field for the HBIM approach concerning knowledge and conservation issues [18]. In this framework, the research presented falls between the second and third approaches described before, focusing on the possibility of developing an HBIM process with high geometric accuracy based on a previous photogrammetric campaign, but at the same time integrating the knowledge through a deep analysis of historical sources, technical reports and conservation state documents. In particular, the case study of the so-called Stylite Tower in the Jordanian archaeological site of Umm ar-Rasas. The Byzantine-age Tower is the latest example of the religious practice of Stylite Syrian asceticism in the Middle East, thus representing a cultural heritage of inestimable value also recognized by UNESCO, which inscribed the site on the World Heritage List in 2004.

Under these premises, applying an HBIM process to the Stylite Tower can be considered a benchmark to test the robustness of this modelling approach both for the systematization of the highly segmented data concerning the Tower and for the production of an easy-to-use visualization tool supporting knowledge and maintenance of masonry historic structures. For this purpose, considering the small dimension of the Tower, the HBIM is developed at the scale of the single masonry block composing the structure. The modelling strategy is entirely customized and comprises (i) the analysis of the historical and contemporary sources regarding the entire life of Tower; (ii) the categorization of information, exploring the diachronic order and the semantic associations; (iii) the philological elaboration of the model with customized informative parameters; (iv) the development of a customized repository and interactive 3D viewer using the interchange format Industry Foundation Classes (IFC).

The paper is organized as follows. The research aims are summarised in Section 2. In Section 3, a brief history and architectural description of the Tower is reported. The methodology and procedure followed in classifying the data, defining the structure of the model and coding of the building elements, as well as the implementation of the HBIM of the Tower, are presented in Section 4. The main results are highlighted and discussed in Section 5. Finally, concluding remarks are outlined in Section 6.

2. Research aim

The main aim of the study is to apply and test the HBIM process to collect, organize, and classify a comprehensive set of heterogeneous historical and technical data concerning the Stylite Tower, building up an interactive 3D visualization framework and a customized repository, allowing the detailed visualization of the geometry of each building element composing the structure together with the spatial visualization of the documents. In this framework, the study has multi-field goals: i) to document the historical evolution of the Tower, updating the conservation state and the ongoing decay process; ii) to develop an accurate 3D geometrical model via a stone-by-stone segmentation of the Tower as a support tool to guide the choices for conservation and restoration interventions; iii) to form an updated customized repository of the studies or interventions already carried out that are valuable for the Umm ar-Rasas archaeological site's management; iv) to exploit the model as a digital tool for the remote fruition of the site and valorization purposes.

3. The Stylite Tower: a brief history and architectural description

In this section, first, some information regarding the history of the Tower, the archaeological surveys and the different research conducted on the structure are reported. Then, an architectural description of the Tower in its current state is provided.

3.1. History

Located in the North complex of the archaeological site of Umm ar-Rasas, the Stylite tower was erected in the Justinian period, first half of the 6th century, by an unknown builder [19]. The discovery and the first analysis of the Umm ar-Rasas ruins date back to the 19th century, providing the first descriptions, the first drawings [20], and the photographic documentation of the Tower [21] (see Fig. 1). As reported by the chronicles of the time, the Tower was a small artefact [21], the masonry was not remarkable [21], and only the top was ornamented [20]. The interior of the Tower was "completely choked up with fallen masonry" [20], and the masonry reported severe damages caused by earthquakes.

Further explorations were performed in the 1930s and 1940s [23], and a broad archaeological campaign was conducted in 1986 by the Studium Biblicum Franciscanum and the Jordanian DOA [24], providing the chronological framework and clarifying the functional attribution of the Tower. In particular, the discovery of a church in the south direction at the base of the Tower supported the religious functional view instead of the defensive one [25]. The Tower was identified as a Byzantine artefact and a unique material evidence of the religious practice of stylite Syrian asceticism in Jordan, serving as a meditating platform for stylite monks, who lived in the cell on the top of the structure, with an original dome-shaped roof not more existing at the time of the archaeological campaign [25]. All the monuments of the Umm ar-Rasas site were protected by the 1988 Antiquities Law administered by the Jordan Department of Antiquities (DOA).[1] Umm ar-Rasas site was nominated to the World Heritage List in 2002[2] and inscribed in 2004,[3] and the statement of Outstanding Universal Value was retrospectively formulated in 2010.[4]

According to the "Umm ar-Rasas site management plan", elaborated by DOA and UNESCO,[5] consolidation works were conducted in 1973 at the foundation level, and some collapsed courses were rebuilt. The first systematic *in situ* analysis campaign for the structural conservation of the Tower was only started in 2006. In 2007, Koellish focused on the bad preservation state of the Tower, advancing the hypothesis of the application of carbon fibre straps together with the renewing of the broken and weathered lintels

[1] Antiquities Law n. 21 of 1988 (amended in 2004) (https://whc.unesco.org/en/statesparties/jo/laws, Accessed February 1, 2024).

[2] Nomination of the old city of Um er-Rasas (Kastrum Mefa'a) for the World Heritage List, February 2002 (https://whc.unesco.org/en/list/1093/documents/, Accessed February 1, 2024).

[3] The decision was adopted at the 28th session of the World Heritage Committee, Suzhou, China 28 June - 7 July 2004 (https://whc.unesco.org/archive/2004/, Accessed February 1, 2024).

[4] Adoption of retrospective statements of Outstanding Universal Value (https://whc.unesco.org/en/decisions/4261, Accessed February 1, 2024).

[5] Umm ar-Rasas Site Management Plan (https://whc.unesco.org/document/167063, Accessed February 1, 2024).

and some stones [26]. In the same year, the first project for the restoration of the Stylite Tower of Umm ar-Rasas was financed by the WHC,[6] followed by the WHC Expert mission conducted in 2008[7]; in 2009, a further project for the investigations and emergency measures for the restoration of the Tower was financed by the WHC.[8]

In 2009–2010, under the patronage of DOA, several small interventions were conducted for the preservation of the Tower, such as replacing some deteriorated stones, filling the wider gaps with stone slabs and arranging some glass slides between some masonry blocks to monitor the displacements [27].

Starting in 2014, different research groups, in collaboration with DOA, have conducted new investigations on the state of conservation of the Tower and its seismic vulnerability through 3D geometrical and geophysical surveys [28,29] and developing several structural models [30–33]. Indeed, the high seismic hazard of this area [34] represents a permanent risk for the structure, which presents evident signs of deterioration. Finally, in 2021, the WHC requested the State Party to submit the final conservation project proposal for the Stylite Tower.[9]

3.2. Architectural description of the Tower

The Tower is in the central part of a rectangular walled court, distancing almost 15 m from the ruins of the church located in the south of the site and the adjacent small building [24]. The Tower is about 15 m high and has a square base cross-section with a side 2.52 m long. As illustrated in Fig. 2, the elevation walls are supported by a stone basement and present 37 rows of dry-jointed limestone blocks. According to a recent archaeological study [19], the limestone blocks are ‘lumachella’ stones, recrystallized carbonate rocks with good mechanical properties. The standard measurements of the blocks may suggest the adoption of a sort of prefabrication technique for the cut of stones. The internal filling of the Tower is made of randomly arranged stone blocks. Conical voussoir-cut stones are located in the middle of some rows, without a regular pattern to stabilize the internal filling.[7]

The upper cell is composed of six rows of dry-jointed limestone blocks with three openings, the largest on the south façade, probably used as a door. The corners are architecturally decorated by cornerstones cut in a semi-circular shape to form half columns. Mouldings feature the upper cornice of the cell, forming carved capitals in the corners. The collapsed curved voussoir-cut stones, lying on the cell floor, bear witness to the original dome-shaped roof. The tower elevation wall features some stone elements with traces of decoration. On the east and the north façades, four crosses in bas-relief are located at rows 11 and 18, in the middle of the cornerstones. A small opening is on the north façade at the base of the Tower to access a small chamber. A square vertical gallery in the west corner connected the chamber to the upper cell. Indeed, this gallery is 45 cm by 45 cm wide and is currently obstructed at the level of the 17th row, presumably after the collapse of the upper cell dome. Finally, the Tower leans dangerously in the northwest direction with an angle of about 2.5° - 3°, as evaluated in [29,32].

[6] Restoration of the “Stylite” tower of Um Er Rasas, January 26, 2007 (https://whc.unesco.org/en/list/1093/assistance/, Accessed February 1, 2024).

[7] WHC Expert Mission Report, Um er-Rasas, 28 June - 8 July 2008, (https://whc.unesco.org/en/list/1093/documents/, Accessed February 1, 2024).

[8] Investigations and emergency measures for the restoration of the Stylite Tower of Um-er-Rasas, February 16, 2009 (https://whc.unesco.org/en/list/1093/assistance/, Accessed February 1, 2024).

[9] WHC State of conservation reports, 2021 (https://whc.unesco.org/en/list/1093/documents/, Accessed February 1, 2024).

4. Materials and methods

The proposed HBIM aims to collect, organize, and classify a broad set of heterogeneous historical and technical data concerning the Stylite Tower, exploiting an easy-to-use visualization framework to support the conservation and valorization of the structure. The HBIM design is entirely customized to the unique features of the Tower, taking into account the standards for the informative and geometrical modelling.

In this case, the HBIM model refers to the Level of Information Need (LOIN) concept, as defined by the in [35,36]. According to the purpose of the HBIM and the limited dimensions of the Tower, the geometric information is detailed at the level of the single limestone block composing the structure. For the inner filling of the Tower, due to the scarcity of information [32], the geometry is instead modelled as a simplified conceptual mass. The alphanumeric information derived from the organization and classification of the heterogeneous collected data concerning the Tower is associated with the single limestone block, according to the data segmentation process explained in the following sections. To ensure the standardization of information management, the general classification of the digital items of the model refers to the ontological international standard defined by CIDOC-CRM [37]. Furthermore, the Italian Central Institute for Restoration (ICR) standards[10] are adopted for the description and coding of the materials and building elements according to their accuracy in the analytical scheduling of archaeological monuments for conservation purposes [38]. Finally, the open international standard of IFC [39] is exploited to support the interoperability of the HBIM with open-source viewer platforms.

The elaboration of the HBIM could be summarised in the following phases: 1) Classification of documents; 2) Definition of information categories and model input data; 3) Definition of the model structure and coding of the building elements; 4) the HBIM modelling.

4.1. Phase 1: classification of documents

Phase 1 focuses on classifying the documents in chronological periods and typology (e.g. iconography, written report, technical drawing, quantitative data). Thus, the collected sources were sorted according to a simplified chronological distinction: historical documents (including the 19th century) and contemporary documents (since the 20th century). The first group of historical documents (HD) includes the descriptions of the Tower provided in the 19th century, subdivided into two sets: A) textual description (exploration reports) and B) iconography (drawings and photos). The second group of contemporary documents (CD) includes a large number of heterogeneous sources, collected into five sets: A) Archaeological campaign reports; B) UNESCO documents[11]; C) On-site surveys; D) Models; E) Scientific literature. An extract of the different typologies of classified documents is shown in Table 1.

4.2. Phase 2: Definition of the information categories and model input data

In general, multiple features of the Tower are discussed in each document set, providing insight into different categories of information. In Phase 2, the documents-derived information is classified

[10] Guide alla compilazione delle Schede MA I livello e II livello (Guide for the compilation of the MA Sheets of I and II levels), (http://www.cartadelrischio.beniculturali.it/, Accessed February 1, 2024).

[11] Available on the website of the UNESCO World Heritage List related to Um er-Rasas (Kastrom Mefa’a) (https://whc.unesco.org/en/list/1093/documents/, Accessed February 1, 2024).

Table 1
An extract of the classified document list, reporting an exemplifying item for each typology.

Group		Set	Typology	Title	Author	Year	Reference	Format	Geometry	Materials	Conservation	History	Public
Historical documents (HD)	**A**	**Textual descriptions**	Book	The Desert of the Exodus: Journeys on Foot in the Wilderness of the Forty Years Wanderings	Palmer	1872	[20]	PDF	G		C	H	X
	B	**Iconography**	Drawing	Tower at Umm Rasas	Palmer	1872	[20]	JPG	G		C	H	X
			Photography	Tower and church from west	Brünnow et al.	1904	[21]	JPG	G		C	H	X
	A	**Archaeological reports**	Paper	Prima campagna di scavo a Um er-Rasas	Piccirillo	1987	[24]	PDF	G		C		X
	B	**UNESCO documents**	Nomination	World Heritage Scanned Nomination - Umm ar Rasas site	DoA, Jordan	2002	fn[2]	PDF	G	M	C	H	X
			Map	Um er-Rasas (Kastrom Mefa'a) - Map of the inscribed property	DoA, Jordan	2004	fn[11]	JPG	G				X
			Mission report	WHC Expert Mission Report, Um er-Rasas, 28 June 8 July 2008	Sicilia	2008	fn[7]	PDF	G	M	C	H	X
			State of Conservation report	State of Conservation Report Um er-Rasas (Kastrom Mefa'a)	DoA, Jordan	2021	fn[11]	PDF			C		X
Contemporary documents (CD)	**C**	**On-site surveys**	Aerial photographs	Aerial photographs	APAAME	2014		JPG	G		C		X
			Technical report	Geotechnical, geophysical and geostructural analysis for conservation of the Stylite Tower	ENEA-ISPRA	2015	fn[11]	PDF		M	C		X
			Digital drawings	Survey 2D drawings	CNR	2016		DXF	G		C		
			Ortophotos	Ortophotos	CNR	2019		TIF	G		C		
	D	**Models**	Structural model	Structural model	CNR	2019		MAT	G	M	C		
			TLS point cloud	TLS point cloud	CNR	2016		e57	G		C		
			MVS point cloud	MVS point cloud	CNR	2019		e57	G	M	C		
	E	**Scientific literature**	Paper	Stability and seismic vulnerability of the Stylite Tower at Umm ar-Rasas	Clemente et al.	2019	[31]	PDF	G	M	C		X

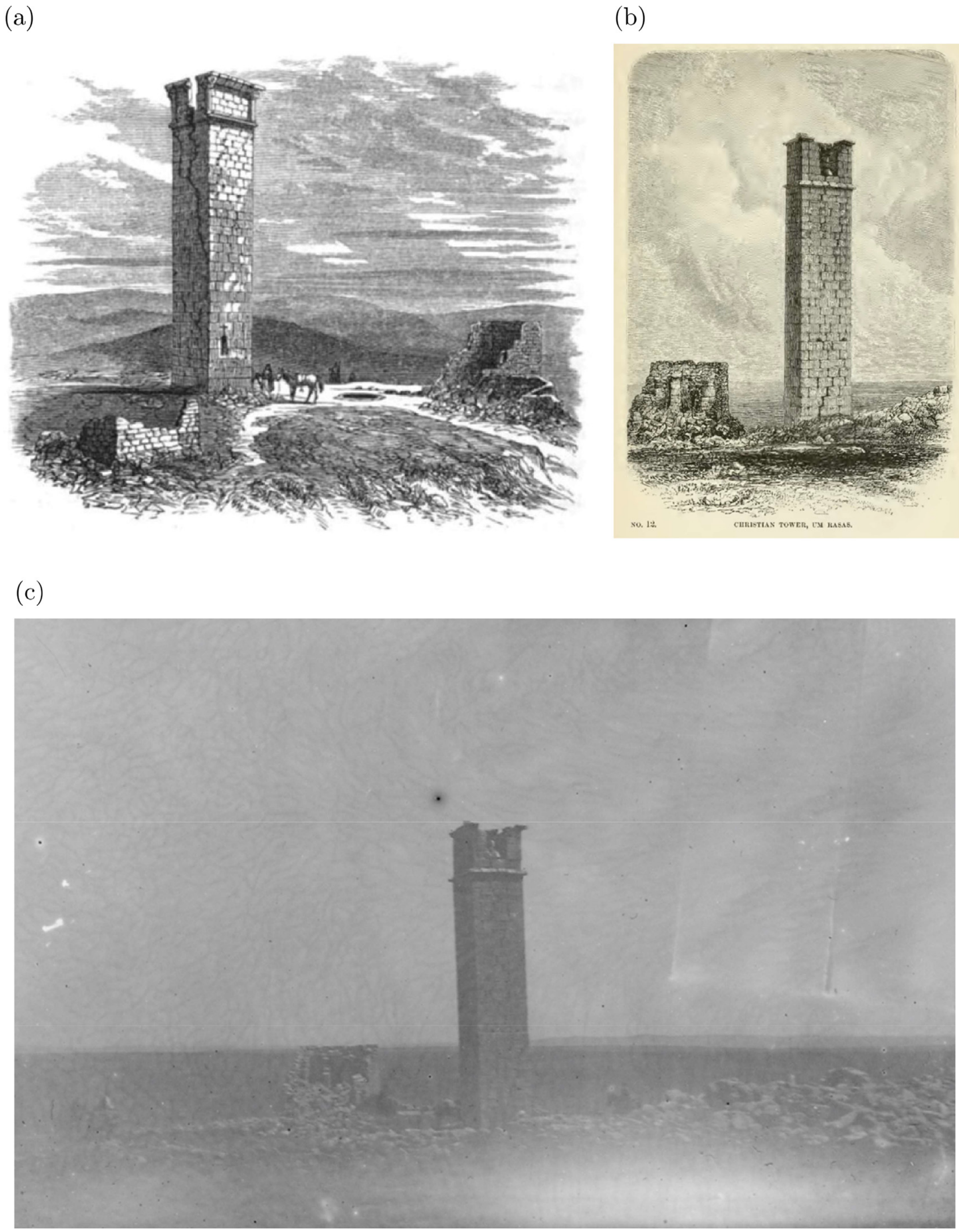


Fig. 1. The Tower in the 19th century: (a) South-east façade [20]; (b) South-west façade [22]; (c) South-west façade [21].

into typologies according to contemporary conservation practices [1]. In particular, the data are arranged in four fields: geometry, material characteristics, conservation state, and structure history. The first three categories of information are directly related to conservation purposes, while the fourth is related to the valorization and dissemination of the structure history.

As shown in Fig. 3, the definition of the informative parameters corresponds to the information categories. Then, the informative parameters are grouped into customized Property Sets that are named according to the CIDOC-CRM standard. The Properties Sets include information about the geometry and the position, the mechanical properties, the current conservation state (e.g. existing, damaged, absent), and, where available, a field related to the document sources, reported via hyperlink. The classified documents are thus stored in a customized repository within a main “Input data” folder. This folder is subsequently segmented according to the main categories of documents and related subcategories.

4.3. Phase 3: definition of the model structure and coding of the building elements

Phase 3 focuses on defining the hierarchical model structure and coding the building elements of the Tower. This phase is a crucial step to ensure the semantics and consistent association between the building elements of the Tower and the cor-

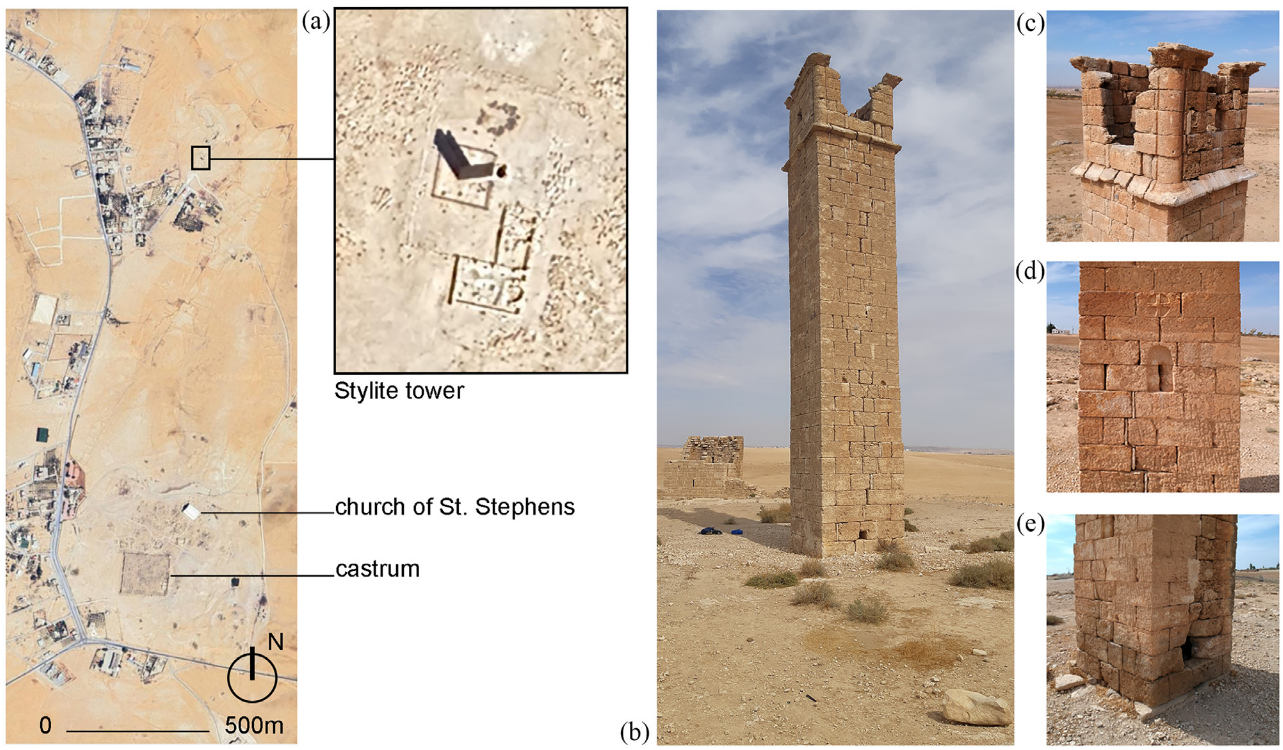


Fig. 2. (a) Aerial view of the site of Umm ar-Rasas; (b) South-west view of the Tower; (c) Detail of south-east side of the upper-cell; (d) Decoration on the east façade; (e) Detail of north-east side of the basement and lower-cell.

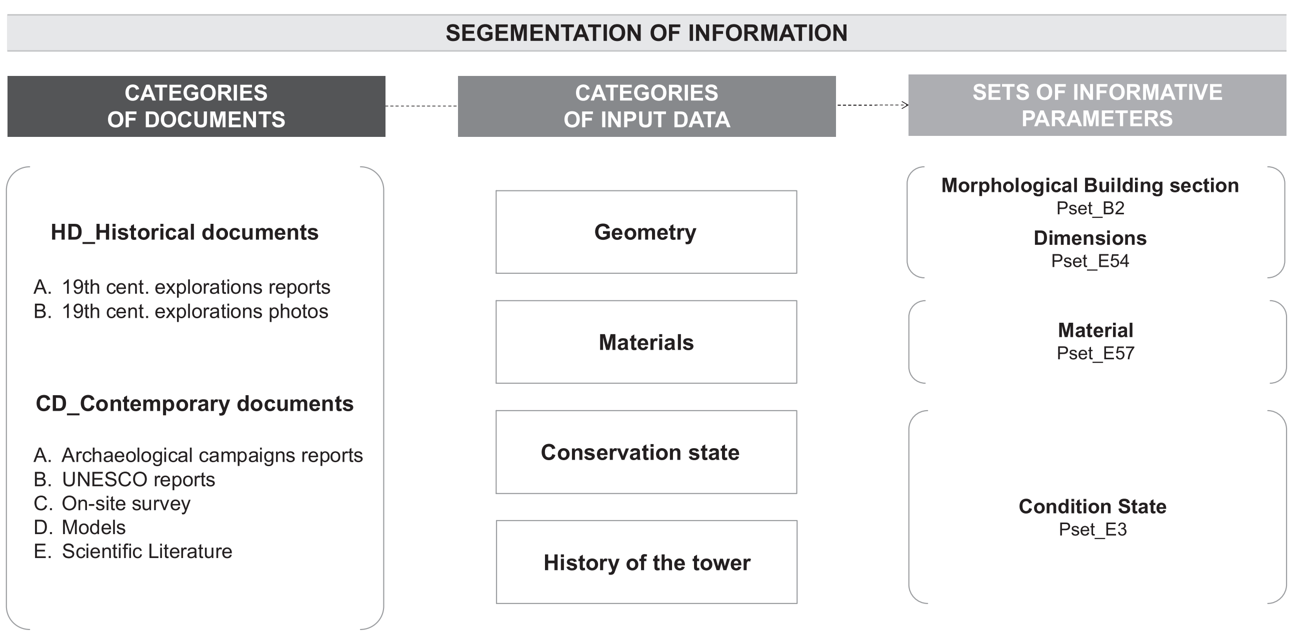


Fig. 3. Segmentation of documents-derived information for model input data.

responding digital items. In order to guarantee the normalization of information management, the general classification of the digital items refers to the ontological international standard defined by CIDOC-CRM. As a framework for structuring and organizing cultural heritage data, CIDOC-CRM is unique compared to other ontologies in representing complex relationships and hierarchies between cultural heritage objects [40]. Furthermore, the base ontology of CIDOC-CRM is complemented by a series of modular extensions designed to support research questions and documentation, such as bibliographic documentation or geoinformatics [41].

In this study, the CRMba extension is adopted, specially conceived to encode metadata about the documentation of archaeological buildings [42]. In particular, the Class E24 "Human-Made Things" hierarchic scheme is adopted for the description of the Tower. According to the hierarchy of the E24 Class, the entire Tower belongs to the subclass E25 "Human-Made Feature", whereas the units of the structure are considered part of the subclass "E22-Human-Made Object". The association with the CRMba extension is also exploited for the description of the building units, referring to the Classes "B2 Morphological Building Section" to include all the limestone blocks. The B2 Class is associated with the

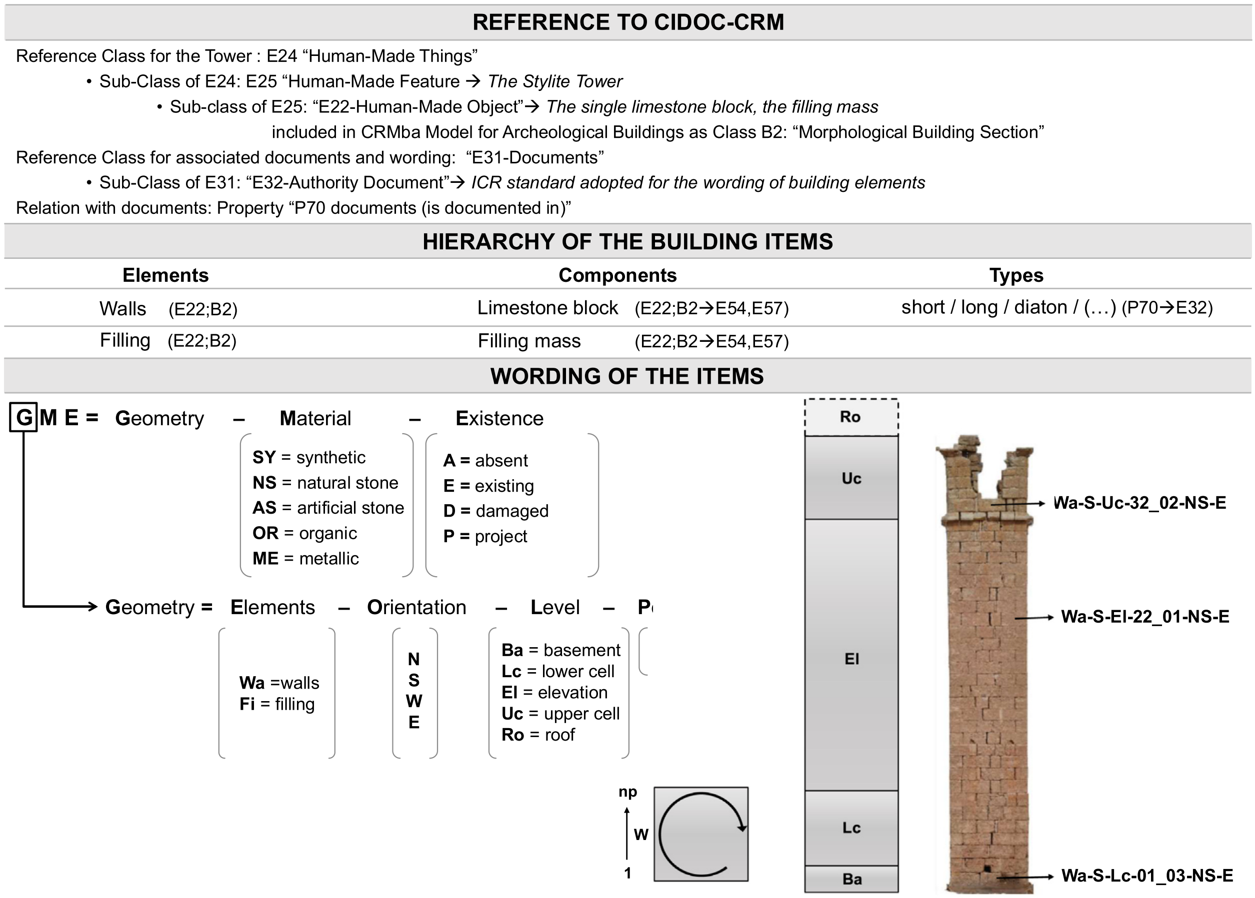


Fig. 4. Diagram of the hierarchy and coding of the building items, reporting CIDOC-CRM adopted Classes (bottom right, orthophoto of south façade of the Tower [32]).

Classes “E54 Dimensions” and “E57 Materials”, used to identify geometrical and material characteristics of the limestone blocks. The association between the Tower items and the related document corpus is described by the class “E31-Documents” and the directly related subclass “E32-Authority Document”. The E32 Class comprises thesauri, authority lists and other documents that define terminology or conceptual systems and, in this specific case, allows the connection of the model structure with the ICR standard adopted to the wording of the elements. Furthermore, the relation between the digital items and the linked data is expressed by the Property “P70 documents (is documented in)” associated with the “E22- Human-Made Object” class.

As illustrated in Fig. 4, the hierarchy of the digital items of the model - belonging to the B2 Class - is organized into “Elements”, “Components”, and “Types”.In particular, two Elements are introduced: “Walls”, which refers to the masonry, and “Filling”, which refers to the inner filling material. Components represent the first sub-hierarchy of the Elements and, in this case, are all the limestone blocks for the Walls, while the entire filling is modelled as a single geometry. “Types” represent the direct sub-hierarchy of the Components and reflect the different typologies of the blocks in elevation (e.g., short, long, diaton), including the ruined vault-shaped blocks of the roof.

Finally, a customized element wording was set up to generate a suitable ID for each item. As shown in Fig. 4, the ID is composed of attribute concatenation of the three fields: “Geometry”, “Material”, and “Existence”. The Geometry field is identified by the Elements, the “Orientation”, the “Level”, and the “Position” of each item. The Material field represents the classes proposed by the ICR standards.[10] The Existence field refers to the classification of the actual condition of each building element, distinguishing the destroyed elements (A), the existing ones not damaged (E) or damaged (D), and the new elements defined by future projects (P). The Geometry and Material fields are permanent, while the field Existence is considered variable, according to the temporal update of the model.

4.4. Phase 4: HBIM modelling

The modelling process of the Tower was conducted by exploiting the interoperability within the following software platforms: Grasshopper®, a plug-in of the Rhinoceros® software, Rhinoceros Inside Revit®, and Autodesk Revit®. The process was divided into two main actions. The first one falls within the definition of the geometric model, decomposing the Tower into its constituent elements. The second one regards the loading of the geometrical model into the HBIM model and the association of the customized informative parameters presented in the previous sections.

In [32], a multi-step geometrical modelling strategy was proposed to achieve an accurate structural model of the Tower, starting from a point cloud obtained from the photogrammetry survey [12] conducted in 2019. By levering this structural model, a procedure via cutting planes was implemented to refine the model until

[12] As presented in [32], the photogrammetric survey was conducted using the DJI Spark MM1A UAV; a total of 202 photos have been collected, following eight vertical trajectories along the façades and corners. The photos have been processed using the MVS matching software, and the reconstructed model has a reprojection error of 0.721 pixels.

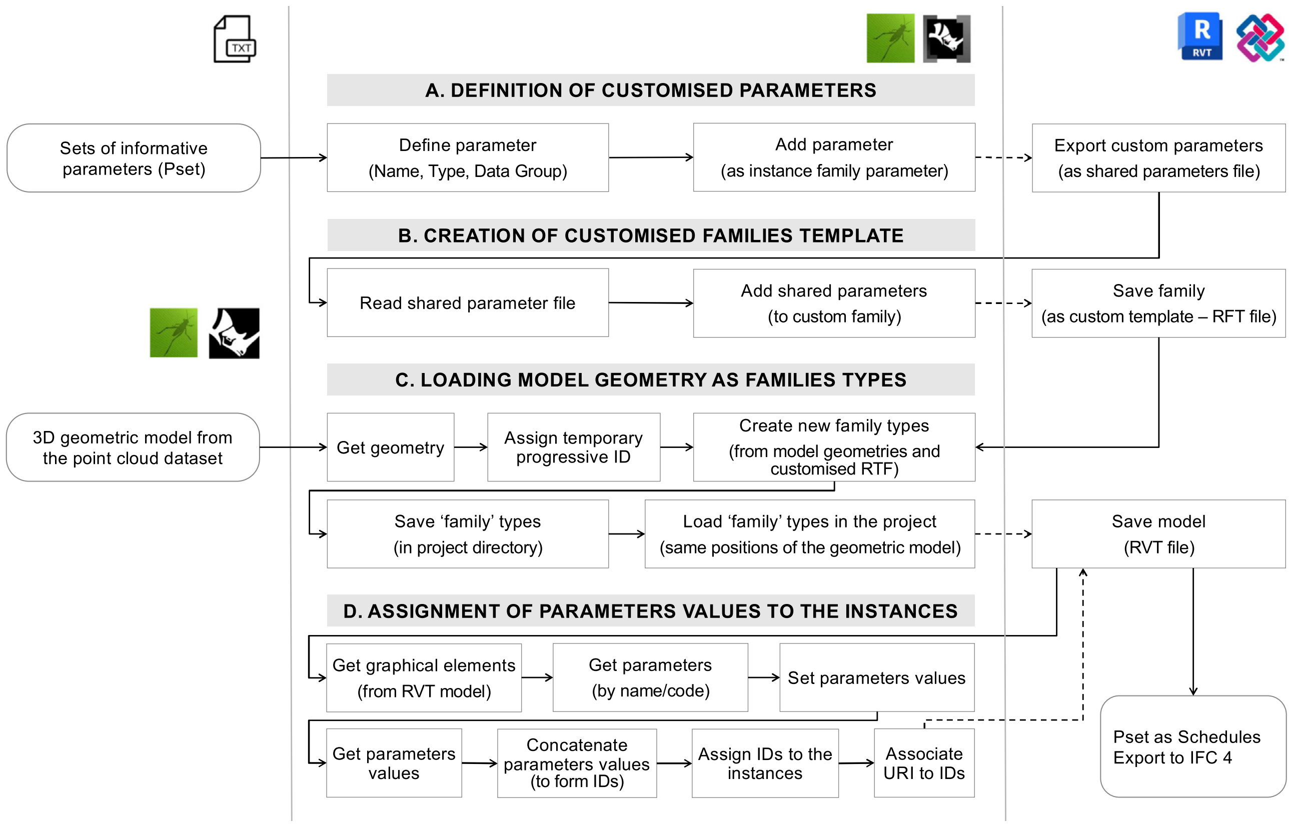


Fig. 5. Diagram of the workflow for the loading and the informative enrichment of the geometric model into the HBIM model. The central section shows the four blocks of operations performed via Rhino Inside Revit code. The dashed arrows represent tasks that must be performed in Revit manually.

the geometry of the individual blocks was defined, using interoperability between Rhinoceros and Grasshopper software. By exploiting the information in the RGB triplet of the individual points of the photogrammetric survey, horizontal cutting planes corresponding to each row of masonry blocks of the Tower were drawn.

Afterwards, taking advantage of both the alternation between long and short blocks of the same dimensions per row and the repetition of the same pattern in elevation, the vertical cutting planes were generated, completing the definition of the faces of the blocks. As regards the upper cell of the Tower, the presence of openings and an irregular pattern of the blocks led to the need for more time-consuming manual operations. Such a procedure allowed the inheritance of the geometric accuracy of the parent structural model of the entire Tower [32], reaching a block-level precision by exploiting also the information deduced from the collected documents (e.g. the diatom voussoir geometry was refined according to the UNESCO mission report[7]). This level of geometric detail is also of fundamental importance to allow subsequent structural analyses using discrete element modelling (e.g. [33,43]).

The second action focuses on the informative enrichment of the geometrical model, using the Rhino Inside Revit plug-in and the Revit platform, as shown in Fig. 5. By using a Rhino Inside Revit code, A) the customized parameters are defined and added to B) the customized families template for the limestone blocks, and C) the geometrical items are associated with a unique family type. Finally, D) the customization of the general Property Set for each limestone block is defined. Furthermore, the code allows the automatic generation of the limestone block IDs and the link to related document sources. The model is developed by exploiting the native functions of the Revit platform. In particular, the "Schedule function" supports assigning specific values to each parameter of the general Properties Set to every single limestone block of the Tower. Furthermore, the function "Exporting Schedule as Property Set" supports the generation of customized IFC.

5. Results and discussion

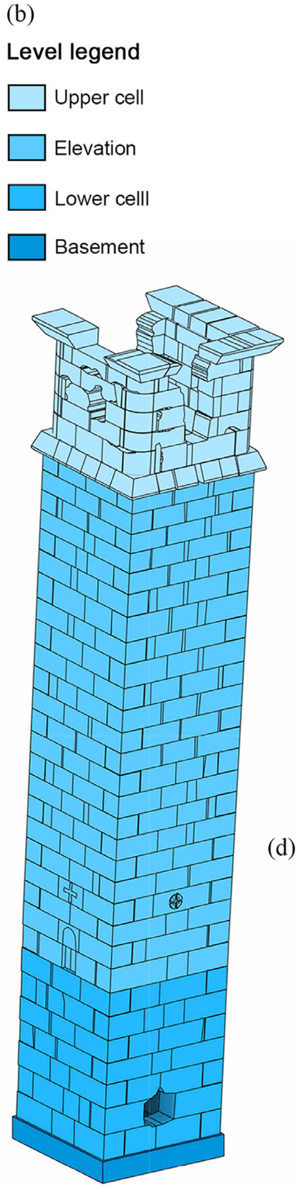
One of the main results of the proposed HBIM is the possibility of performing qualitative and quantitative analyses of the state of conservation of the structure. In particular, on the one hand, the accurate geometric description of the individual limestone blocks and the information parameters collected allows, for example, to automatically tabulate the main geometric characteristics of the blocks and their spatial position, exploiting the schedules function (see Fig. 6 (a)). On the other hand, Figs. 6 (b) and 6 (c) show the possibility of querying the model and applying filters, therefore showing the different "Levels" into which the structure has been divided or the different types of blocks for each façade. Finally, a synthetic output of an example query on "Existing" and "Damaged" limestone blocks is presented in Fig. 6 (d). The table divides the number of blocks pertaining to the two categories according to the block type. The damage blocks are listed, exploiting the results of visual analysis conducted on photographic and photogrammetric sources.

Exploiting open-source platforms, the IFC allows the interactive visualization of the model, embedding customized informative data and the direct link to further documents stored in the customized repository. As shown in Fig. 7, the IFC provides the interactive 3D visualization of the model where a customized set of informative parameters and links to the related documentary sources enrich the geometry of each limestone block. In this way, the IFC viewer represents an easy-to-use tool to access the document collections, explicitly referring to the 3D representation of the Tower.

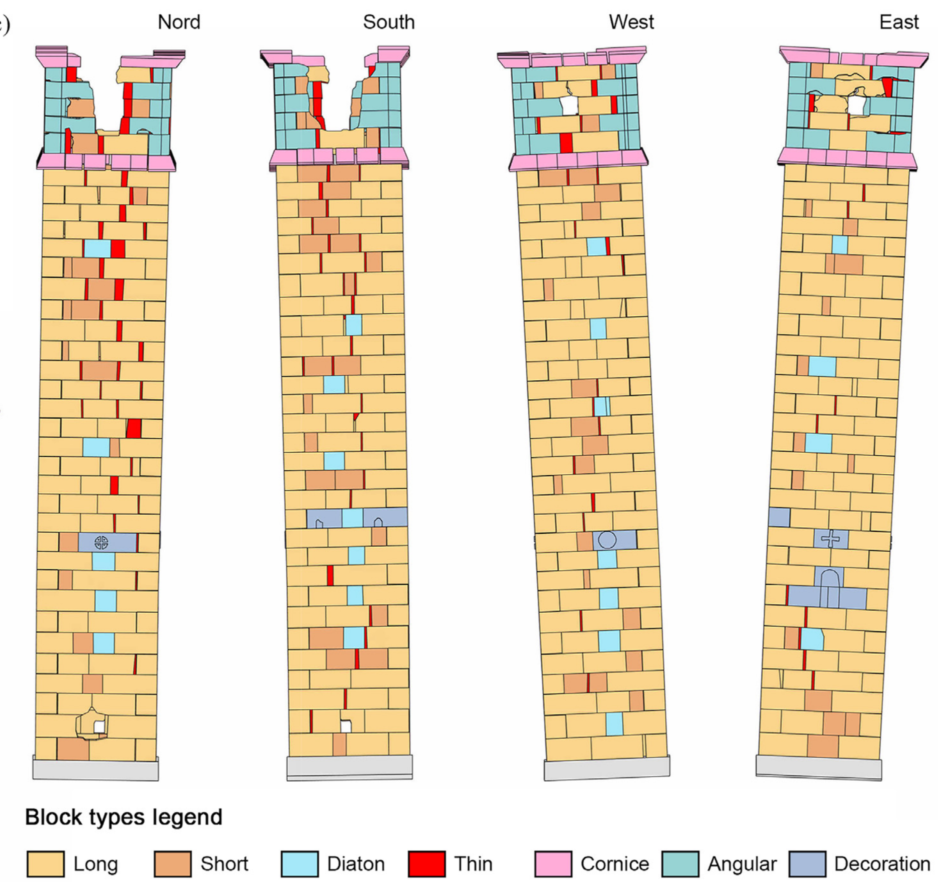
(a)

Limestone Blocks Properties									
B2.04	B2.03	B2.05	B2.07	E54.01	E54.02	E54.03	E54.04	E54.05	E31.01_Historical documents
Nord façade									
Wa-El-N-30_05-NS-E	Long	El	30_05	0.86 m	0.37 m	0.44 m	0.29 m²	0.13 m³	www.domain.it//Wa-N-El-30_05-NS-E
Wa-El-N-11_02-NS-D	Decoration	El	11_02	1.22 m	0.44 m	0.44 m	0.46 m²	0.20 m³	www.domain.it//Wa-N-El-11_02-NS-D
Wa-Lc-N-06_02-NS-D	Diaton	Lc	06_02	0.44 m	0.48 m	0.44 m	0.31 m²	0.14 m³	www.domain.it//Wa-N-Lc-06_02-NS-D
Wa-Lc-N-01_02-NS-D	Short	Lc	01_02	0.66 m	0.51 m	0.44 m	0.31 m²	0.14 m³	www.domain.it//Wa-N-Lc-01_02-NS-D
Wa-Uc-N-36_01-NS-P	Added	Uc	36_01	0.07 m	0.34 m	0.44 m	0.02 m²	0.01 m³	www.domain.it//Wa-N-Uc-36_01-NS-P
Wa-Uc-N-37_01-NS-D	Cornice	Uc	37_01	1.33 m	0.26 m	0.66 m	0.28 m²	0.18 m³	www.domain.it//Wa-N-Uc-37_01-NS-D
Wa-Uc-N-35_03-NS-D	Angular	Uc	35_03	1.02 m	0.39 m	0.44 m	0.31 m²	0.13 m³	www.domain.it//Wa-N-Uc-35_03-NS-D

(b)



(c)



(d)

Block type	Count							
	Nord façade		South façade		West façade		East façade	
	Existing	Damaged	Existing	Damaged	Existing	Damaged	Existing	Damaged
Angular	0	4	0	6	0	5	0	5
Cornice	0	6	0	4	6	4	6	2
Decoration	0	9	0	4	1	1	0	4
Diaton	2	3	3	4	4	4	3	1
Long	28	35	35	26	35	35	58	13
Short	8	9	11	15	8	12	11	4
Added *(Project)*	36	/	28	/	20	/	14	/
Total	74	66	77	59	74	61	92	29

Fig. 6. Outputs of the Stylite Tower HBIM: (a) Extract of the table related to limestone block properties, exploiting the schedules function; (b) Coloured map of the different "Levels" of the Tower; (c) Coloured map according to the blocks types; (d) Exemplifying query on "Existing" and "Damaged" limestone blocks.

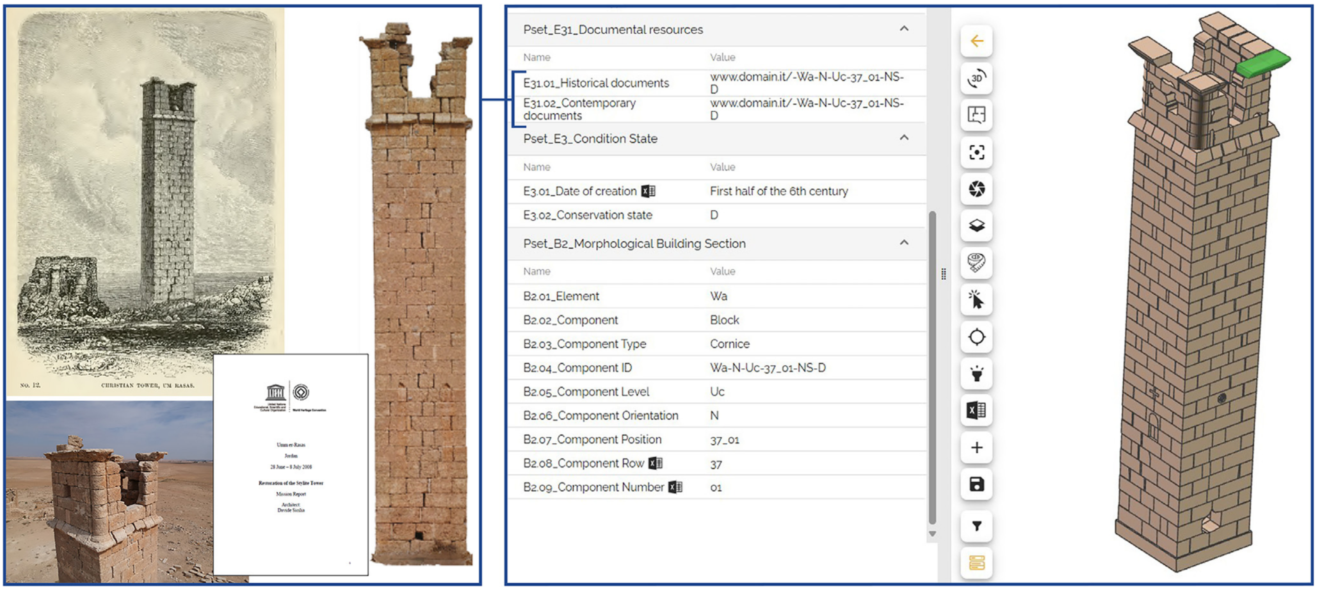


Fig. 7. Interactive 3D visualization of the model for a single limestone block: (panel right) an open-source viewer and (panel left) pertained informative data (images from Tristram [22], Pierdicca et al. [32] and UNESCO document[7]).

From a future perspective, a limitation of the proposed HBIM is the absence of a model of the Tower foundation and the soil. Starting from the geophysical surveys conducted in [29] and technical reports in UNESCO documents,[11] this aspect can be integrated into the current model, enriching the level of knowledge of the structure and allowing the use of the model as input for geotechnical and interaction soil-structure analyses. Moreover, updating the current repository to a structural database represents a natural development of this research. On this point, a non-negligible obstacle is given by the general problem of sharing documents published and unpublished by different authors and the management, security and responsibility of the database itself.

Finally, the integration of the HBIM in Geographic Information Systems (GIS) and WebGIS platforms, such as the ones respectively presented in [44,45], can be exploited to upscale the proposed methodology for the analysis of a broader set of structures within the archaeological site of Um ar-Rasas. In this sense, using a relational-spatial database can effectively support the use of queries to correlate the single instances of the model to the related document sources via defined IDs. Furthermore, the exploitation of a more user-friendly web-based platform can support the availability of the model to different categories of users involved in the safeguard and valorization process.

6. Conclusions

In this paper, a customized HBIM approach for the knowledge, conservation, and valorization of heritage structures is presented. The HBIM of the Stylite Tower in the archaeological site of Umm ar-Rasas is proposed as an exemplary case study for documentation and maintenance activities, site management and dissemination purposes.

The first goal of the presented HBIM is the organization of heterogeneous and fragmented sources concerning the history and the actual state of conservation of the Tower. In the framework of the HBIM approach, the research contributed to establishing modelling protocols and information management criteria addressing heterogeneous data sets, producing a digital archive embedding an easy-to-use visualization tool. The modelling process demonstrates effectiveness for the representation of irregular geometries of masonry structures, reaching a stone-by-stone segmentation of the Tower.

Second, the HBIM produces a flexible tool to perform fast qualitative and quantitative analysis concerning the actual state of the structure, supported by the spatial visualization of documents. According to the scale of the investigated structure, the presented workflow could adapt, changing the base unit of the model, ranging from the single limestone block to the main structural elements (e.g. walls, arches, vaults).

Third, the application of the proposed workflow to the Stylite Tower remarks the possibility of generalizing the process for the subset of ancient heritage structures featured by heterogeneous sources and complex geometry. In particular, the generation of the IFC allows the extraction of geometrical and informative data in an open-source format, supporting the future development of the model from a multidisciplinary point of view.

Finally, the proposed HBIM could be enriched through virtual and augmented reality, focusing on the transformations of the structure throughout history, e.g., propose the reconstruction of the fallen vaulted roof. In this way, HBIM can be exploited for dissemination and touristic purposes via user-friendly applications and devices.

CRediT authorship contribution statement

Claudio Intrigila: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Ilaria Giannetti:** Conceptualization, Methodology, Formal analysis, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing. **Elena Eramo:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Roberto Gabrielli:** Conceptualization, Methodology, Writing – review & editing. **Giovanni Caruso:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

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