



DATA-DRIVEN CONSERVATION ACTIONS OF HERITAGE PLACES CURATED WITH HBIM

ACCIONES DE CONSERVACIÓN DE LUGARES PATRIMONIALES A PARTIR DE DATOS GESTIONADOS CON HBIM

Tuğba Sarıcaoğlu^{a,*} , Gamze Saygi^b 

^a Dokuz Eylül University, Tinaztepe Campus Buca, 35390 Izmir, Turkey. tugbasaricaogluts@gmail.com

^b Amsterdam School of Historical Studies, University of Amsterdam, Kloveniersburgwal 48,
1012 CX Amsterdam, The Netherlands. g.saygi@uva.nl

Highlights:

- This paper illustrates the potential of scan-to-HBIM notion for heritage sites by employing an innovative data-driven approach to conservation actions.
- This research offers an HBIM workflow for the sophisticated representation of heterogenic archaeological datasets.
- This study creates a digital twin of the archaeological building remains and offers a method tailored for future monitoring and conservation.

Abstract:

Digital surveying tools provide a highly accurate geometric representation of cultural heritage sites in the form of point cloud data. With the recent advances in interoperability between point cloud data and Building Information Modelling (BIM), digital heritage researchers have introduced the Heritage/Historic Information Modelling (HBIM) notion to the field. As heritage data require safeguarding strategies to ensure their sustainability, the process is closely tied to conservation actions in the architectural conservation field. Focusing on the intersection of the ongoing trends in HBIM research and the global needs for heritage conservation actions, this paper tackles methodological pipelines for the data-driven management of archaeological heritage places. It illustrates how HBIM discourse could be beneficial for easing value-based decision-making in the conservation process. It introduces digital data-driven conservation actions by implementing a novel methodology for ancient building remains in Erythrae archaeological site (Turkey). The research ranges from a) surveying the in-situ remains and surrounding stones of the Heroon remains with digital photogrammetry and terrestrial laser scanning to b) designing a database system for building archaeology. The workflow offers high geometric fidelity and management of non-geometric heritage data by testing out the suitability and feasibility for the study of material culture and the physical assessment of archaeological building remains. This methodology is a fully data-enriched NURBS-based (non-uniform rational basis spline) three-dimensional (3D) model—which is integrated and operational in the BIM environment—for the holistic conservation process. Using a state-of-the-art digital heritage approach can be applied from raw data (initial stages) to decision-making about an archaeological heritage site (final stages). In conclusion, the paper offers a method for data-driven conservation actions, and given its methodological framework, it lends itself particularly well to HBIM-related solutions for building archaeology.

Keywords: building archaeology; digital archaeology 3D heritage database; conservation decisions; Historic Building Information Modelling (HBIM); NURBS (non-uniform rational basis splines); scan-to-HBIM

Resumen:

Las herramientas topográficas digitales proporcionan una representación geométrica muy exacta de sitios patrimoniales en forma de datos (nubes de puntos). Con los avances recientes de interoperabilidad entre nubes de puntos y modelado de información de la construcción (BIM), los investigadores en patrimonio digital han introducido la noción de modelado de información de la construcción patrimonial/histórica (HBIM) en este campo. Como los datos patrimoniales requieren estrategias de salvaguardia que garanticen su sostenibilidad, el proceso está íntimamente ligado a acciones de conservación en el campo de la conservación arquitectónica. Teniendo en cuenta las últimas tendencias en investigación HBIM y las necesidades globales de las acciones de conservación patrimonial, este artículo afronta el flujo metodológico de la gestión basada en datos de sitios patrimoniales arqueológicos. Se introducen acciones de conservación basadas en datos que implementan una metodología novedosa en los restos edificados del sitio arqueológico de Erythrae (Turquía). La investigación aborda tanto la fase desde a) el topografiado in situ de los restos y las piedras circundantes de los restos de Heroon con fotogrametría digital y escaneado láser terrestre, hasta b) la fase del diseño del sistema de bases de datos en arqueología de la arquitectura. El flujo de trabajo ofrece alta fidelidad geométrica y de gestión de datos patrimoniales no geométricos; también prueba la idoneidad y viabilidad de cara al

* Corresponding author: Tuğba Sarıcaoğlu, tugbasaricaogluts@gmail.com



estudio de la cultura material y a la evaluación física de los restos de edificios arqueológicos. El modelo tridimensional (3D) enriquecido con datos basados en NURBS (*'non-uniform rational B-splines'*), se demuestra que es operativo en el proceso de conservación integral; este trata desde los datos sin procesar hasta la toma de decisiones sobre un sitio arqueológico-patrimonial, utilizando un procedimiento digital puntero. En conclusión, el artículo presenta un método orientado a acciones de conservación basadas en datos y, dado su marco metodológico, se presta particularmente bien a soluciones relacionadas con HBIM en arqueología de la arquitectura.

Palabras clave: arqueología de la arquitectura; bases de datos patrimoniales 3D; decisiones de conservación; modelado de información de la construcción histórica (HBIM); NURBS (B-splines racionales no uniformes); escaneado-a-HBIM

1. Introduction

Heritage data, which enables recording, analysis, decision-making, and management, is the key to the conservation of heritage sites. The sustainability of heritage data, whether it is implicit, tacit or explicit, is critical for the holistic conservation process and for taking important conservation decisions (Fredheim & Khalaf, 2016).

The capacity of three-dimensional (3D) capturing tools and techniques such as laser scanning and structure from motion (i.e., photogrammetry) to allow the capture of highly accurate geometrical representations of heritage places has been proven. Because these tools are bundled within the computer-aided design (CAD) software in the construction disciplines, heritage data and digitalization have been relatively interoperable with data generated from digital surveying. The data referred to here consists namely of point clouds, rectified images, digital surface models (DSM) and orthophotos.

Conventionally, the data, and particularly orthophotos, have been used as a reference for two-dimensional (2D) drafting in the CAD environment. Following the development of interoperability tools to migrate data from point cloud formats to CAD software, digital outputs have significantly improved; these tools have improved the 3D digital modelling of heritage sites, for example. Subsequently, the ability of Building Information Modelling (BIM) software such as Autodesk Revit and Graphisoft ArchiCAD to operate point clouds for vectorial referencing prompted a novel development called "as-built BIM" (Tang, Huber, Akinci, Lipman, & Lytle, 2010). Utilizing BIM for heritage sites has become a novel area of interest in the cultural heritage discipline, and this practice is now referred to as Historic/Heritage Building Information Modelling (HBIM). The term HBIM was first coined by Murphy, McGovern & Pavia (2009) in a study of an 18th-century building façade. Since then, the method has been widely expanded in the discipline with novel applications at different scales: archaeological object findings, monuments, and historic urban patterns, etc.

Despite the ground-breaking advances over the last decade, the integral management of conservation-driven heritage data has not yet been achieved. This is because heritage data require a 3D management environment to store geometries and the capacity to integrate conservation-specific data and sustainable archiving. The difficulty is more challenging when the object is non-uniform, which is typical of archaeological heritage sites.

This study investigates the heritage information management process, from data capture to decision-making, by designing a data-driven workflow for planning conservation actions. It offers a methodological solution

to integrate data-driven capacity for heritage places, particularly archaeological sites, by providing a fully functioning modelling framework. It provides state-of-the-art high geometric accuracy of the physical properties of the heritage site and uses a data-driven strategy to incorporate conservation-action-specific schemes. It entails a solution which crisscrosses various levels of conservation actions in the complexity of the recording and interpretation processes, from its materials to its construction, and takes in material, building elements and volumetric scales. It, therefore, explores the integration of geometrical and non-geometrical properties into data-driven conservation actions.

2. Mapping the field: HBIM approach

BIM is a digital information management system which is generally implemented for construction projects. BIM has extensive functions for the construction of buildings (Azhar, 2011). The function of a typical BIM extends from producing 2D drawings to the operational management of the project's finances. Recent literature has indicated two essential parameters that define a BIM as an HBIM; the specific modelling procedures for *in-situ* heritage sites and the integration of heritage-related analytic information, such as material culture and deterioration patterns (Jouan & Hallot, 2019; Banfi et al., 2022). To generate a discipline-specific overview of the advances in the cultural heritage field, we revisited recent HBIM studies, comprising 45 papers published in scientific outlets from 2009 to 2021. We examined the various capacities and characteristics of the methods used, such as the cases' architectural typologies and historical classification, modelling workflows, and output formats, and their relation to conservation actions.

The architectural typologies of the cases were extensively varied, from studies conducted solely at an elemental scale (for example, an arch) to studies conducted at the structural scale, such as those dealing with the complex architectures of palaces or cathedrals complexes. Only six of these studies (13%) experimented with archaeological heritage sites, four of which were from before the common era (Achille, Lombardini, & Tommasi, 2015; Bagnolo, Argiolas, & Cuccu, 2019; Bosco, D'Andrea, Nuzzolo, & Zanfagna, 2019; Garagnani, Gaucchi, & Gruška, 2016); studies of non-uniform heritage geometries are quite scarce.

Surveying methods for heritage resources have also been documented. These include terrestrial laser scanning (TLS), photogrammetry, and technologies such as unmanned aerial vehicles (UAV) and wearable mobile laser systems (Sun & Zhang, 2018).

Furthermore, we observed three different 3D creation approaches: hypothetical, semi-hypothetical and authentic, according to the accuracy level of the geometrical representation of the surveyed surface. Geometric

modelling follows a reverse engineering methodology by moving from physical to virtual multi-dimensional representations. In this study, the term 'hypothetic model' corresponds to the minimal geometric accuracy of the modelled assets without any survey (Lee, Kim, Ahn, & Woo, 2019) or without integrated surveys (Sztwiertnia, Ochalek, Tama, & Lewińska, 2019). The two latter geometric modelling approaches implement the 3D surveys with higher geometric fidelity; this is a proven method in the cultural heritage field, particularly in the case of scan-to-BIM studies (Rabbani, van den Heuvel, & Vosselman, 2006; Volk, Stengel, & Schultmann, 2014; Bassier, Hadjidemetriou, Vergauwen, Van Roy, & Verstrynghe, 2016; Angulo, Pinto, Rodríguez, & Palomino, 2017; Capone & Lanzara, 2019).

Studies have shown that modelling approaches such as non-uniform rational basis spline (NURBS), mesh, and CAD are chosen on the basis of the relevant computing and design functions. Eleven of the studies (25%) directly dealt with at least one conservation action and employed point cloud-based surface modelling (with NURBS-based software). Among them, the oldest case was a 7th century vault (Banfi, 2020), the study of which dealt with heritage knowledge at the building element scale. Various papers have pointed out that when using *polysurfaces* as solid geometries, as with volumes made with NURBS surfaces, the accurate geometric representation of the object is quite achievable; this has been studied in the geometric modelling field, for example in finite element analysis for structural analysis (Banfi, 2019; Banfi et al., 2022; Barazzetti, 2016; Brumana et al., 2017, 2018).

Additionally, Jouan & Hallot (2019) have highlighted the notable lack of decision-making processes in HBIM studies by illustrating how HBIM discourse could be beneficial for easing value-based decision-making in the conservation process. However, their study suggests the generation of theoretical preservation management protocols for preventive conservation by creating digital twins within the BIM environment.

Significant efforts have been made to import BIM terms and their practical significances into HBIM. For instance, the term LOD (level of development) is discussed by several researchers (Banfi, Fai, & Brumana, 2017; Brumana et al., 2018; Castellano-Román & Pinto-Puerto, 2019). Although the LOD in BIM illustrates the information modelling stages which concern a building's lifespan from its design to maintenance, Castellano-Román & Pinto-Puerto (2019) have argued that chronological LOD implementation cannot be conducted for HBIM since heritage artefacts are "past" time-related assets, and have introduced the term Level of Knowledge (LOK). This term covers the stages of identification, protection and dissemination, advanced research, conservation and intervention, and comprehensive management. Similarly, Banfi and others (2016) have proposed a new term, ReverseLODs, which represents heritage buildings' level of development combined with other levels of heritage information. The LOD scheme, at present, is still in effect since existing denominations do not extend to somewhat ambiguous data, which exist in many shapes and forms such as scripts and noniterative architectural features that heritage sites carry.

Banfi et al. (2017) has developed a novel approach to troubleshooting the issue of model accuracy in HBIM and introduced the term *grade of generation* (GoG) to distinguish geometric modelling approaches according to

their geometric precision, particularly for the BIM platform. Banfi's study states that GoG 1-8 covers primitive and new-design-compatible modelling techniques, while GoG 9-10 covers digitally captured surface and survey modelling approaches. Consequently, point cloud-based advanced modelling falls into Banfi's GoG 9-10 category.

Managing heritage data within HBIM is different from designing a building with BIM. This difference is more evident when the object is non-uniform, which is particularly significant for archaeological heritage places. Undeniably, 3D capturing technologies provide highly accurate virtual 3D representations as digital point clouds of the surveyed artefact. However, attempts to fully integrate point clouds into HBIM have resulted in architectural models which behave functionally merely as scaled and detailed geometric projections. BIM software, in general, allows generative modelling, but is incapable of detecting point clouds and converting them into 3D models. Besides, built-in BIM object generation remains primitive, and the modelling logic is limited to new design elements and construction systems.

There is an increasing interest in developments which expand the capabilities of HBIM, such as element modelling (Barazzetti, Banfi, Brumana, & Previtali, 2015), HBIM element library experiments (Baik, Alitany, Boehm, & Robson, 2014), information mapping (Chiabrande, Lo Turco, & Rinaudo, 2017), mixed-reality applications (Banfi, 2021), the development of generative modelling methodology (Brumana et al., 2018), and even the illustration of a road map for holistic conservation practices (Brumana et al., 2020) and building archaeology (Banfi et al., 2022). Despite these significant attempts, using HBIM for data-driven conservation actions remains an open field of study. As Volk and others (2014) have also highlighted, the software-level structures of BIM environments are still not fully able to encompass the life cycle of heritage information. The process of analysing any non-uniform heritage objects, from surveying to decision making, is indeed a complex research problem. In particular, HBIM could serve as a data-driven model supporting future (conservation) analysis and decision-making, and serve to produce a more democratic, transparent and sustainable system for the preservation of heritage information.

3. The case study: Heroon Remains at Erythrae

Erythrae is one of the 12 Ionian cities of Asia Minor, and is located on the Karaburun peninsula in İzmir in modern Turkey. Historical research indicates that there has been a significant settlement at Erythrae since the early bronze age.

The case subject to this study, the remains of Heroon, is situated in the northern part of the Erythrae archaeological site. The name Heroon derives from the Greek word *'ἱρόων* and signifies sacred places in the forms of tombs or shrines of important people of the time (Andronikos, 1980). Heroon bears a significant value in that it represents the ancient architectural culture of Erythrae. For instance, the materials used for the building were taken from the quarry of Erythrae itself, and the construction system shows a sophisticated approach for the time.

The *in-situ* remains of Heroon are very uneven and complex in terms of their geometry, and the building system and heterogeneous material used to increase the challenge. The diversity of material deterioration and structural damage at this site means that it is a typical subject for conservation actions.

Today, the ancient settlement of Erythrae is partially absorbed under a village named Ildiri. On the one hand, this means that the site is a multi-temporal and multi-layered living settlement. On the other hand, the remains are mainly located within private properties, making it impossible to perform any excavation work as there are legal barriers to performing any excavation work beyond surface cleaning and organizing scattered remains such as stone elements.

Despite the excavation campaigns conducted in the Erythrae archaeological site since 1965, the only published archaeological information relating to Heroon is the transcription of a stone-carved script. According to Engelmann and Merkelbach's (1972) transcription, the script contains a vague mention of a Heroon somewhere close to Agora, and the building is dated to 340 BC (Fig. 1). Although the script is eroded and does not directly contain any other information on Heroon (including its location), an excavation team decided that the subject of the script is Heroon, since there are no other remains that even resemble Heroon's structure.

As of 2019, our knowledge about this peculiar site has been limited to that transcription because of the lack of further historical or architectural research. The present study demonstrates the results of the thorough recording and visual interpretation of the remains at Heroon. It focuses on the *in-situ* remains of the building, which are located on a rectangular area of approximately 10 by 18

m, and 156 pieces of scattered stone blocks located around it (Fig. 2). This paper also provides the first and only architectural and archaeological interpretation of Heroon, which has a unique architectural character given its unexampled (or unrepresented) typology within the site and the region

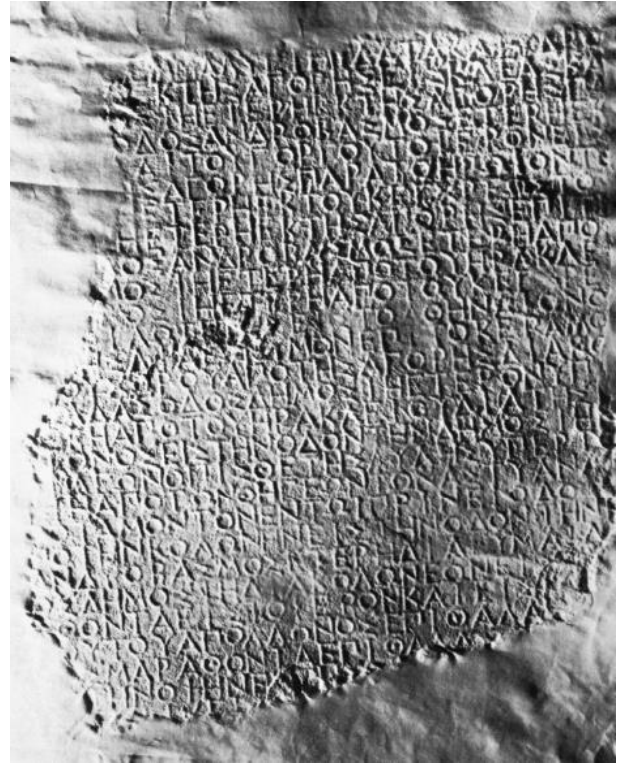


Figure 1: Script 151 (Source: Engelmann & Merkelbach, 1972).



(a)



(b)



(c)

Figure 2: The Heroon remains: (a) bird-eye view of the *in-situ* remains; (b) a view showing the surface erosion due to winds from the west; and (c) a 3D modelling view demonstrating material deteriorations.

4. Curation of conservation actions with HBIM

The conservation actions taken comprised the recording of the *in-situ* material culture, the analysis of its spatial and material properties (such as deteriorations, deformations, and alterations) and the intervention decisions taken to ensure the sustainable preservation of the heritage artefacts. This process provided both geometric recordings of the physical properties of the site and conservation-related interpretations demonstrating the heritage site's architectural and archaeological nature, material culture, and cultural and scientific significance. In doing so, we obtained sophisticated tools for use in the decision-making process as well as transparent heritage information and knowledge interpretations.

In this paper, we re-examine the data-driven conservation actions according to the concept of *data metamorphosis*, defined by Baker (2012) as "the processes of combination and association through which data become transformed into useful information". This concept entails a comprehensive process in which unstructured raw data are gathered and converted into structured datasets, forming information, generating knowledge, and making it available for those seeking to understand heritage sites' history, physical configuration, and condition.

We revisited this conceptual pipeline of heritage curation for the dynamic management of digital heritage data. Tammaro (2016) defines digital curation as providing reliable valorisation of digital data and information management and usage either now or in the future. Heritage data and information tend to be heterogeneous, and heritage experts have been interested in digital curation (Sayão, 2016). Recent digital heritage management initiatives such as *cyber archaeology* consider heritage curation as an integrated part of archaeological heritage management policy (Stanish &

Levy, 2013). This paper develops and implements a fully operational workflow for curation. In Figure 3, we present the virtual life cycle of heritage data curated by HBIM, and the following sections explain the workflow in detail.

4.1. Data acquisition

The first conservation action is data acquisition, namely the surveying of the asset(s). This entails recording the geometrical properties, dimensions, texture, colour, and geographical information of the asset(s) in their "as-is" condition. It involves methods of capturing the digital data of the physical properties and state of the asset(s) and methods of capturing context in order to collect intangible data, such as the historical background of the heritage places.

Initially, Sarıcaoğlu & Köşklük Kaya (2021) employed photogrammetry and range-based laser scanning in tandem as data acquisition methods for surveying the geometrical properties of the building remains at Heroon. Besides, Sarıcaoğlu & Köşklük Kaya (2020) demonstrated the capacity of the photogrammetric method for documenting free-standing scattered stone elements on-site (Fig. 4).

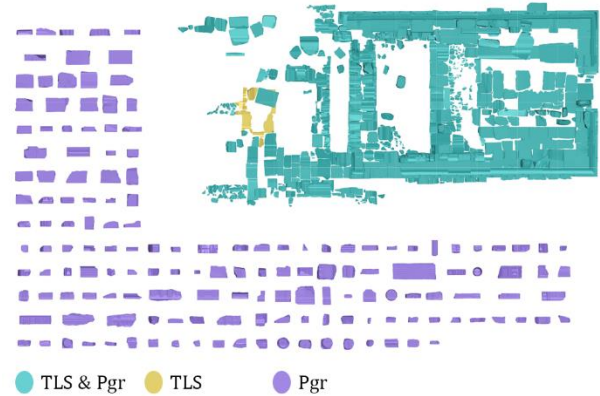


Figure 4: 3D surveying method of the remains of Heroon.

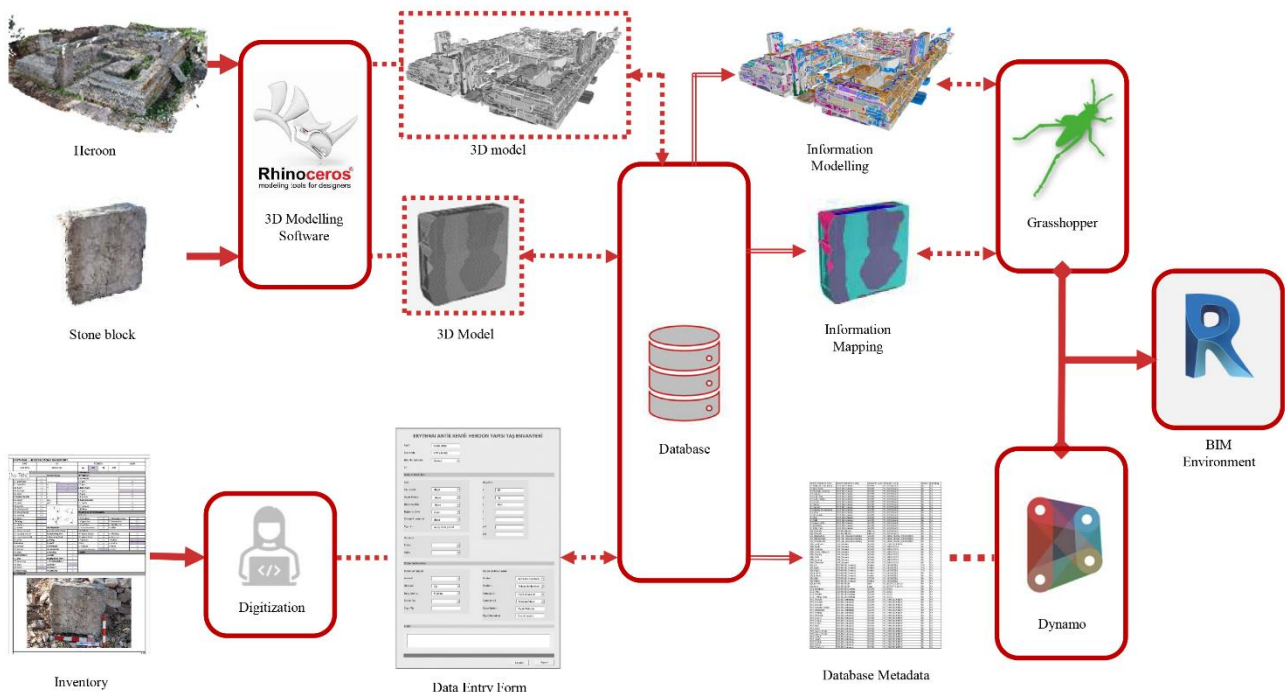


Figure 3: The HBIM workflow of the study, from survey to BIM environment.

The laser scanning of the *in-situ* remains resulted with 24 coloured, high-resolution scans. A ground-based photogrammetric survey by digital camera resulted in 2716 photos. The point cloud data deriving from photogrammetry aligned, scaled and georeferenced, based on the TLS point cloud.

The visual interpretation of the remains during the observatory fieldwork provided the basis for an inventory of the remains' material culture and physical condition. This conceptual inventory is intended to form a multi-model database of the heritage site. The inventory corresponds to the site's properties, including typology, dimensions, and architectural details such as material type and deterioration patterns per stone block.

4.2. Data processing

The data processing phase consisted of database development and geometric modelling. This phase was heavily dependent on previous data acquisition from 3D surveys and field research. For the dense point cloud generation, we aimed at a model deviation up to a few millimetres for achieving adequate geometric accuracy for the stone surfaces. Primarily, surveyed raw data were converted into metadata as 3D point clouds and orthophotos. Simultaneously, the data from the inventory were digitized as well. The geometric modelling was then conducted, which comprised the integration of data from the inventory.

1.1.1. 3D surveying metadata

The aligned and scaled point clouds derived from multiple surveys allowed the execution of orthophoto generation using the default resolution and positioning parameters offered by PointCab v.3.9 software. This direct approach made it possible to avoid digital data loss and provided stable texture references for geometric modelling and analysis. Employing this method was particularly helpful for texture quality and detail because the white balance was off and the light was bright on the day of the TLS survey. The photogrammetric survey remedied these issues. We used both high-accuracy geometric surveys and coloured orthophoto sets to align TLS with photogrammetry.

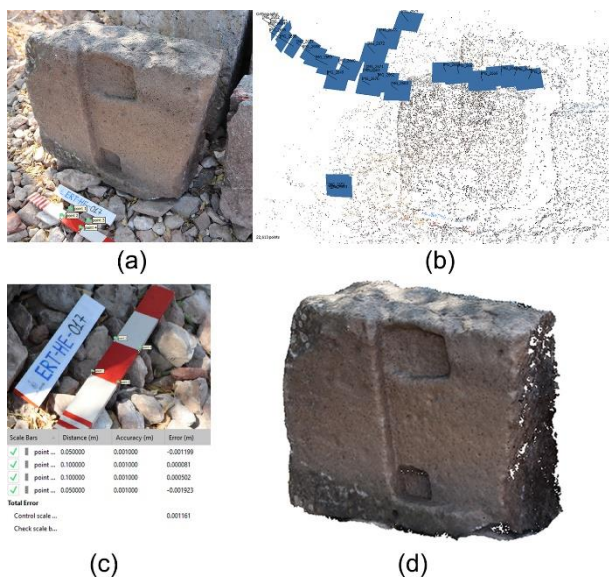


Figure 5: Stone block data processing: a) image of the stone; b) point cloud generation and camera positions; c) reference bar for scaling; and d) final cleaned dense point cloud.

We implemented independent photogrammetric data acquisition and processing for each scattered stone element. As a result, we could clean and position them separately in the geometric modelling phase (Fig. 5).

4.3. Information management

In the previous phases, raw data and structured data were captured. We then integrated the acquired heritage information and analytical data from this phase onwards by employing a data-driven synthesis and decision-making process.

This module has a preliminary step: the geometric model integration into the BIM environment. As our geometric objects corroborate with GoG 9-10 category, and heritage-specific BIM elements are not built-in in the software, we imported the NURBS-based models into the Revit 2020 as a generic model family type. The stone elements were added to the Revit individually, whereas the *in-situ* remains were retained in bulk. It is also worth mentioning that the purpose behind generating GoG 10 category was not only to have a high level of geometric fidelity but also to employ a high-level capacity for semantic enrichment and non-geometric data management, for instance, when simulating intervention decisions.

1.1.2. Database design

We remodelled the inventories consisting of on-field visual interpretations into a data entry form using programming (Visual Basic in Microsoft Excel 2019). This step established a relational database that could be easily integrated into BIM software using the built-in visual programming language (Dynamo Version 2.3). The generated database of the referenced scattered stones and *in-situ* remains of Heroon was then ready to be integrated into the geometric model for information mapping and other multi-level conservation action plans (Fig. 6).

The inventory sheet contained a detailed visual survey of the objects, which was tailored to the site. From physical aspects such as tooling traces, elemental typology, and dimensional features to the assessment of the material condition and architectural relevance, information was laboriously entered into the inventory for the database. This extensive work was subsequently digitized. For utilization purposes, we created a data entry form to convert the inventory data into a database. This implementation meant that the inputs were interoperable between the database and the BIM environment.

1.1.3. Geometric modelling process

The geometric modelling of the *in-situ* remains and stone elements of Heroon was realized using reverse engineering. To tackle interoperability and parametric transference between geometric modelling and BIM software, a NURBS-based modelling program was used.

The BIM environment could understand the polysurfaces as built-in forms of BIM entities. These generative modelling elements, or *families*, correspond to element typologies such as walls, roofs and floors. However, this does not always cover the requirements of heritage sites, especially when it comes to a non-uniform 4th century BC building as the Heroon remains. For example, Heroon has walls, but representing them in one category as 'the wall' will not serve to inform

conservation actions. Instead, treating each stone element in the wall as a separate structural feature created architectural units which were appropriate for conservation interventions. Moreover, the generative drafting of the walls in the BIM software was not applicable because of their varying and distinct geometries. Therefore, for an archaeological site such as Heron, the individual stone pieces composing the masonry structure of the walls require individual assessment, and as such handling remains as part of the modelling process. Although the system's robustness was somewhat cumbersome for both ends of the equation—the experts and the computers—we tackled this issue by importing 3D models as a mass element into the BIM environment.

This study is based on geometric modelling of both 3D point cloud data and generated orthophotos. As such, geometric surface modelling of the in-situ remains was prepared for information management—namely, holistic analysis in 3D. To facilitate this modelling, we implemented semi-automatic profile extraction and point cloud segmentation using CloudCompare and orthophoto tracing within the geometric modelling software, with Boolean operations as well as a point cloud to NURBS conversion, and generated a 3D model consisting of the 1011 individual stone elements that compose the *in-situ* remains of Heron (Fig. 7). We implemented the same modelling procedure individually for the scattered stone blocks, resulting in a total of 156 elements representing these scattered blocks (Fig. 8).

ERYTHRAE : HEROON STONE INVENTORY									
DATE		ID	POSITION				NAME		
03/09/2019		ERT-HE-153	KN	GS	DE	BW			
A. PHYSICAL ASPECTS					B. MATERIAL				
I. Traces		II. Dimensions			III. TYPOLOGY				
a. Tooling	b				a. Andesite				
a.1. anathrosis	b.1				a.1. pink				
a.1. scarnillus	b.2				a.2. grey				
a.3. luster	b.3				b. Limestone				
a.4. bossage	b.4				b.1. grey				
a.5. other	b.5				b.2. pink				
b. Surface Details					b.3. yellow				
b.1. script	b.1	r.1			c. Conglomerate				
b.2. relief	b.2	r.2			c.1. brecc				
b.3. profile	b.3				c.2. paving				
b.4. chisel (small)	b.4				d. Rubble				
b.5. chisel (large)	b.5								
b.6. nesting	b.6				IV. MATERIAL DETERIORATION				
b.7. other	b.7				I. CAUSES				
c. Bracing					a. Salivation				
c.1. clamp	c.1				b. Vegetation				
c.2. dowel		II. POSITION			c. Vandalism				
c.2. clamp channel	c.2				d. Factors Movement				
c.3. carrying (metal)	c.3				II. RESULTS				
c.4. carrying (wood)	c.4				a. Fracture (deep)				
c.5. other		e. Surface/Finishing			b. Fracture (hair)				
d. Bonding		f. Opening (var)			c. Abrasion				
d.1. mortar	d.1				d. Filling				
d.2. plaster	d.2				e. Wall				
d.3. other	d.3				f. Orthostat				
e. Arc. Element		g. Roofing			h. Rupture				
e.1. step	e.1				i. Scaevola				
e.2. opening	e.2				j. Chronose alteration				
e.3. layer	e.3				C. NOTES				
e.4. other	e.4								
f. Other Traces		k. Structural (var)							
		l. Structural (hor)							
		m. Other I							
		n. Other II							
		o. Other III							

ERYTHRAE ARCHAEOLOGICAL SITE DATA ENTRY FORM

Date:

ID:

Remain Location:

English:

Physical Aspects

Traces:

Surface Details:

Bracing:

Bonding:

Arc.Element:

Position:

Structural:

Material Aspects

Material:

Limestone:

Conglomerate:

Rubble:

Other:

Material Deteriorations:

Causes I:

Causes II:

Results I:

Results II:

Other Causes:

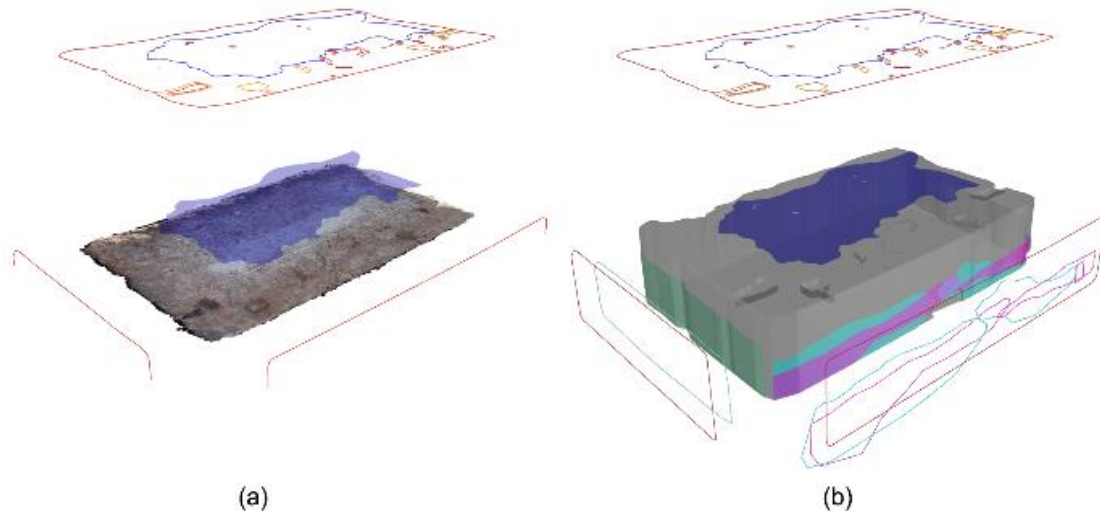
Other results:

Notes:

(a)

(b)

Figure 6: Database design: a) inventory sheet; b) data entry form.



(a)

(b)

Figure 7: 3D polysurface modelling of a stone element: a) orthophoto based; b) point cloud profile extraction and final polysurface.

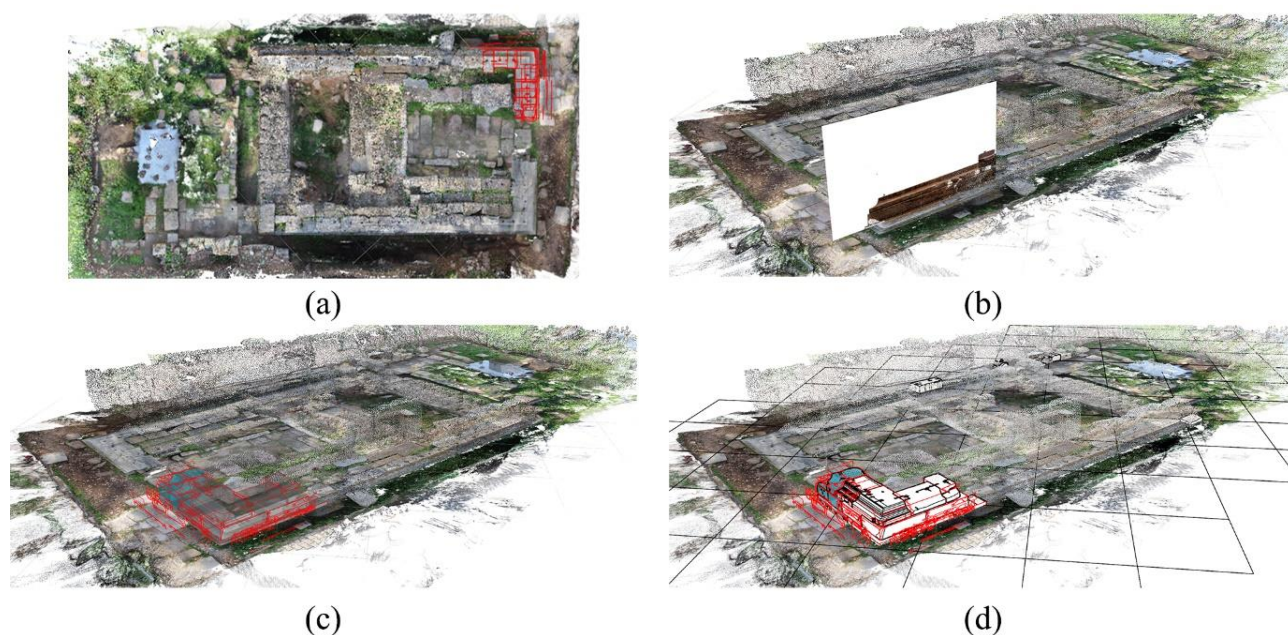


Figure 8: 3D polysurface modelling of the *in-situ* remains of Heroon: a) top view orthophoto; b) 3D orthophoto placement; c) Boolean operations; and d) final surface model of the remains.

We completed the geometric modelling in NURBS-based modelling software (McNeel Rhinoceros 7) for both the 3D *in-situ* remains of Heroon and the scattered stone elements. The information levels in the 3D model were represented by layers and corresponding geometries, in this case as polysurfaces, for each conservation action. Grasshopper v. 5.3.2, a built-in Rhinoceros visual programming language for parametric creation, assisted the conversion of the geometry for migration into the HBIM environment. While modelling of the stone elements was included in the same workflow as modelling of the *in-situ* Heroon remains, the heritage information generated from the database was integrated from the geometric modelling software into the BIM environment in a different way. The data categories were pulled as a list from the database and converted to a parametric Revit family that entailed the properties of the objects. With that procedure, conducted using Dynamo (Version 2.3), the database from the fieldwork was fully integrated into Autodesk Revit 2020.

1.1.4. Information mapping

The information interpreted during the fieldwork regarding the heritage assets' physical aspects and material culture was included in the modelling process. This provided a basis for the 3D representation of conservation actions.

As conservation action measures, analysis of the heritage data included the study of material typology, material deterioration, structural system, structural deformation, and construction phases. We conducted an all-inclusive building archaeology analysis. For instance, Figure 9 illustrates the diversity of materials found *in-situ*, based on visual interpretation and heritage-specific knowledge. Figure 10 demonstrates the material usage in 3D space. Since this research also extends to the spatial scale when analyzing the archaeological remains, Figure 11 introduces another fundamental level by examining the roles of the buildings in terms of their positioning within the remains. This analysis enabled us

to provide a depiction of the spatial relations of both free-standing elements and the *in-situ* remains at scientific and data-driven levels.

Acquired, interpreted, and structured heritage information calls for sustainable organizational measures for the holistic data-driven conservation process. The management of the analytic information—structuring, linking and organizing it—resulted in novel findings. This newly accessed metadata entailed heritage information related to the as-found identification of the heritage assets. Applying information management to Heroon and the stone elements resulted in five primary outputs: (i) the analysis of the spatial relations of the building; (ii) visual analysis of material typologies; (iii) the deteriorations and deformations; (iv) the deciphering of the authentic design phases representing the building restitution study; and (v) intervention decisions for the physical safeguarding of the heritage assets.

The spatial analysis of Heroon was established on the basis of the analyses conducted in the location and construction phases. This re-examination of the conducted investigations benefited the new information generation process, especially by filling in gaps relating to Heroon's typology—its potential past. This practice recalled the displaced (*spolia*) elements, threshold stones, and translocated elements, particularly cornerstones which provide a reference for the original size of the building.

1.1.5. Intervention decisions

Heritage assets are exposed to physical threats due to their locations. These threats can cause material deterioration, loss, structural deformation, and damage. Intervention measures are necessary to avoid dire outcomes. With the help of this 3D model analysis, decisions about each conservation issue could be made and, most importantly, threats could be easily remedied accordingly.

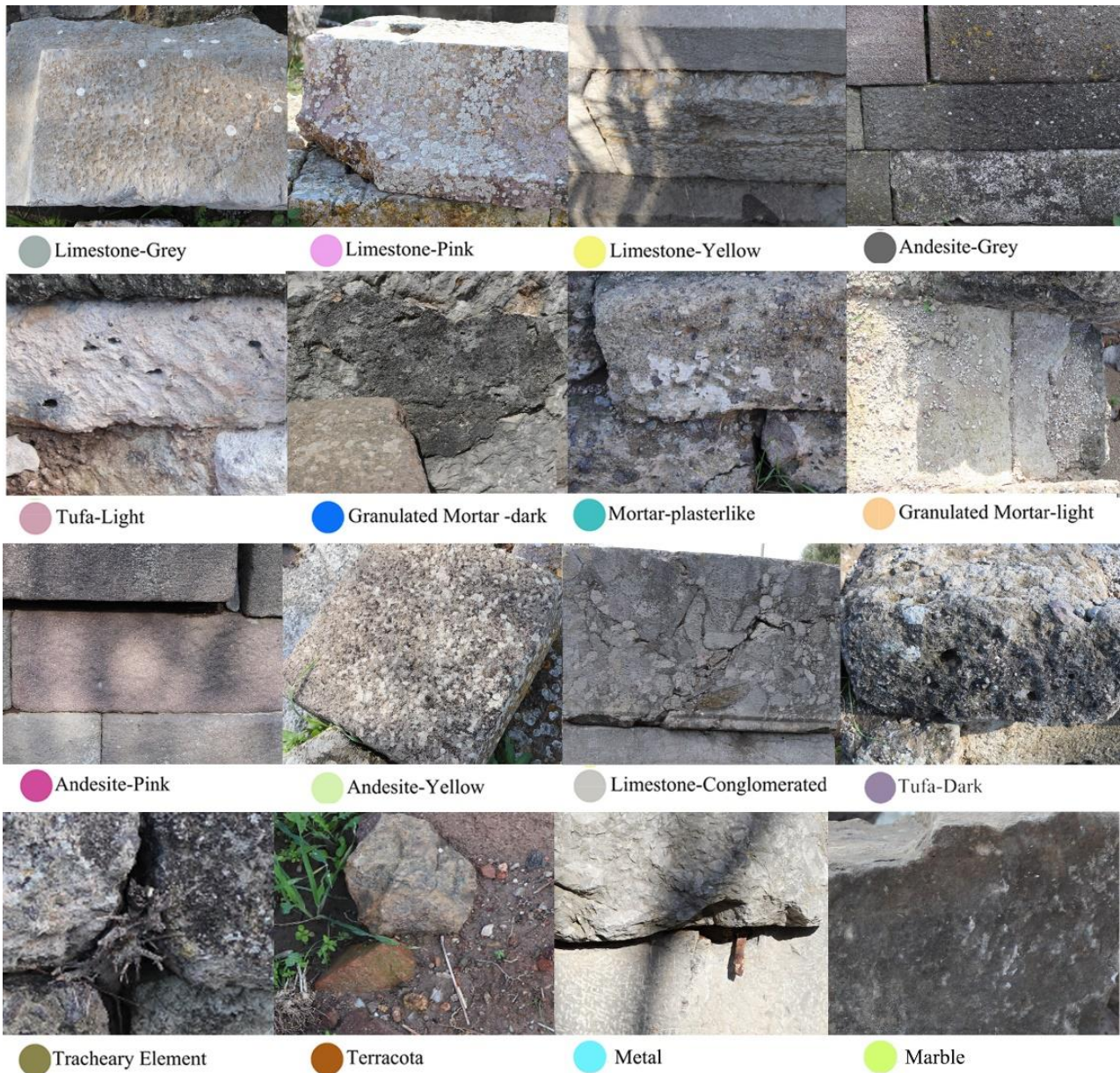


Figure 9: Material typologies at the site.

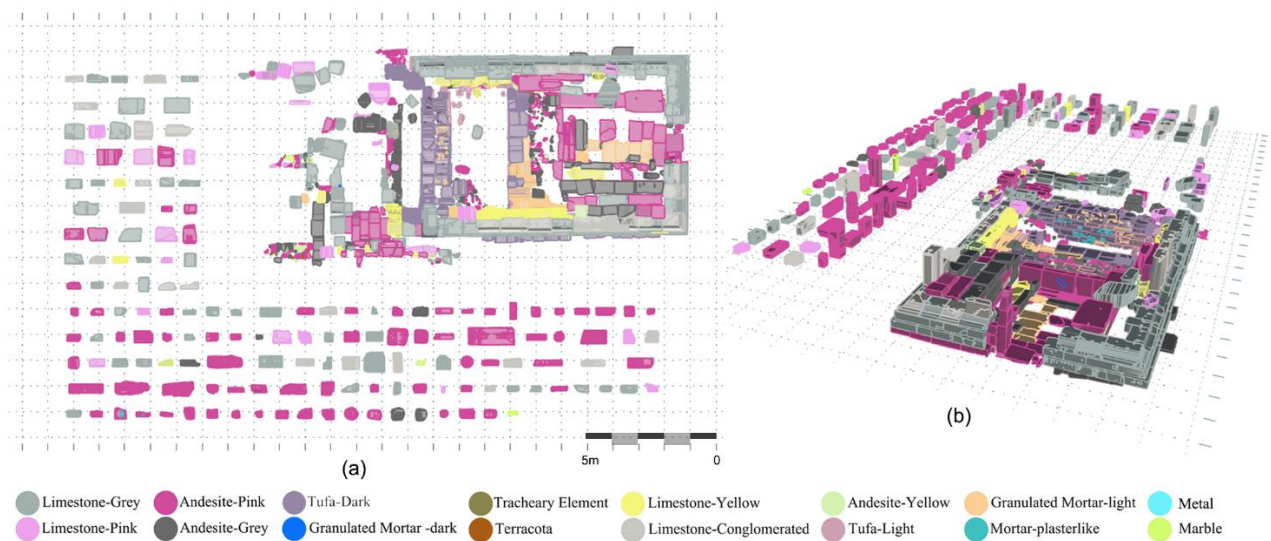


Figure 10: 3D information mapping of material analysis.

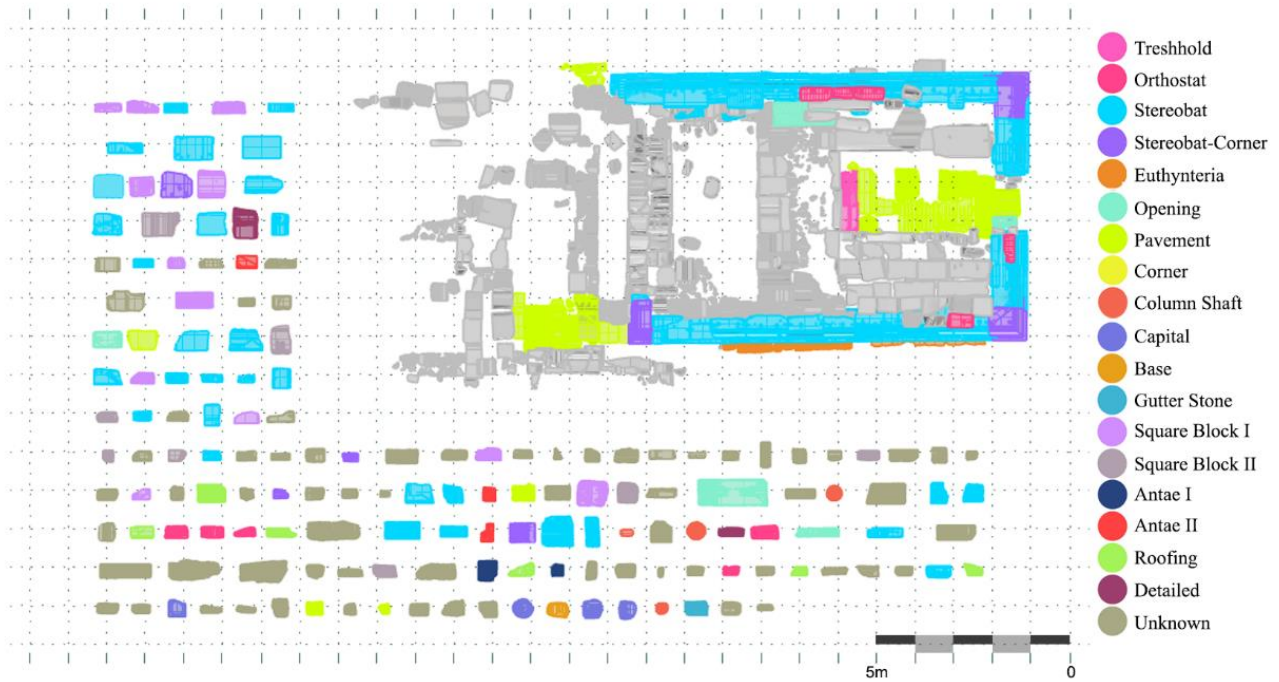


Figure 11: 3D information mapping of the spatial significance of building elements.

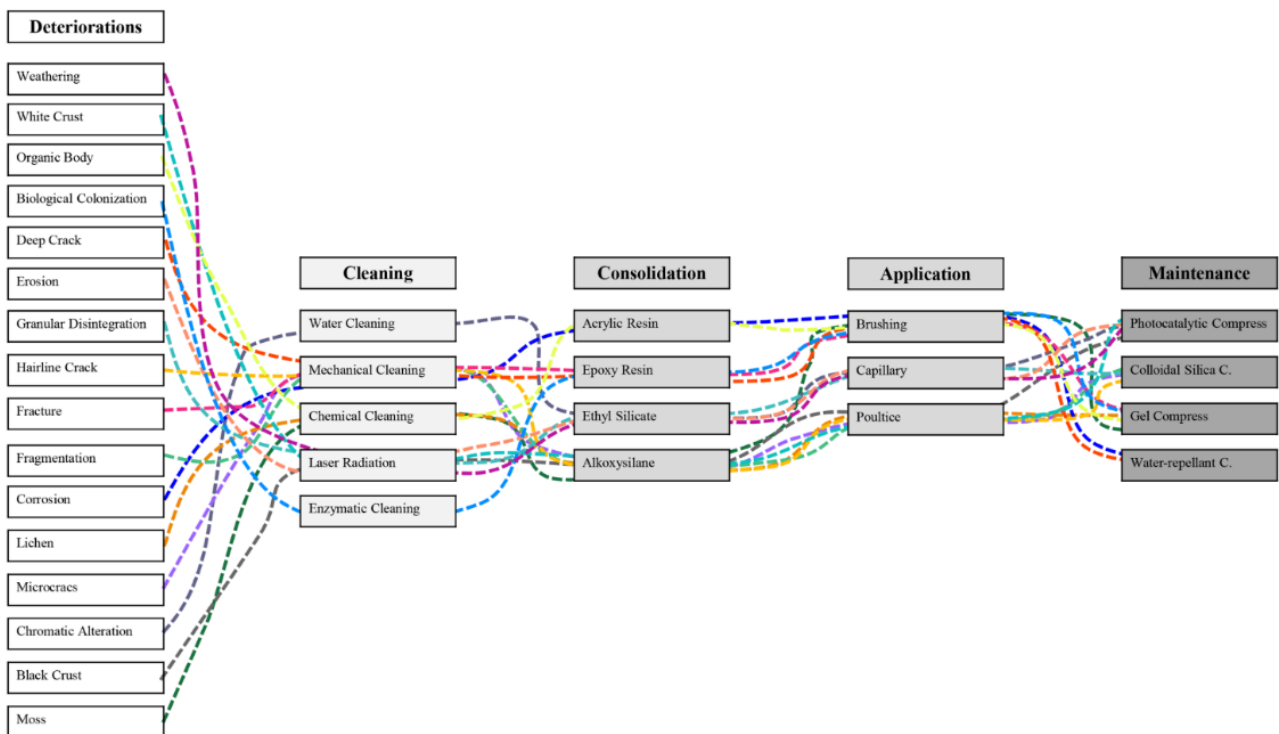


Figure 12: Network design of the intervention decisions for the material deterioration: a) analysis; b) cleaning; c) consolidation; d) consolidation application methods; and e) maintenance steps.

For Heroon and the stone elements, this process was implemented separately at material and structural levels. These decisions were also based on the material typology of the decaying features. For example, although material damage can be manifested in similar ways, like disintegration, deterioration handling procedures differ. Epoxy-based injections are appropriate for andesite stones, for instance, but not particularly helpful for mortar.

Intervention decisions for material deterioration, instances of which fell into 16 different classifications, were taken in three steps: (i) cleaning, (ii) consolidation, and (iii) maintenance. A set of procedures was specified for each of these steps, such as which chemicals to use and how to implement them (Fig. 12). For instance, we observed heavy lichen formation located in the far northern part of Heroon (Fig. 13). Lichen creates a biofilm on the surface

of stone elements. It can induce both physical and biochemical reactions, e.g. by the emission of oxalic acid, which can result in surface erosion and more dire problems like the complete loss of assets. To remedy lichen formation, material and location-specific intervention decisions must be made. At Heroon, we decided to address this deterioration first by chemical cleaning with acidic solutions, then by consolidation with alkoxysilane poultice, which has been found to be an appropriate long-term decontamination method. We chose gel-based surface agents to ensure deep and time-released protective surface penetration.

We illustrated the application method to prove how this detailed methodology could be utilized for each process. This procedure administered programming and heritage-specific algorithms, which specified information and data and provided a reference for the decision-making process (Fig. 14). The intervention decision-making process for the structural issues was organized in two steps: assessment of urgency level and selection of application method (Fig. 15). Primarily, the urgency levels of the structural deterioration threats were identified depending on the immediate risk that they posed for visitors and in terms of heritage loss. Next, structural system analysis was conducted on areas of intermediate safety, followed by the lowest priority areas. These procedures were generated using a network design similar to that used in the aforementioned material-level interventions. It is worth mentioning that this step-by-step decision-making process was applied individually to the 156 free-standing stones, because the system was bound to the multi-modal database and shared the digital environment simultaneously.

5. Discussion and results

The spectrum of conservation actions ranges from documenting to reconstructing heritage sites. Heritage sites, particularly archaeological heritage sites, have complex tangible and intangible properties. Heritage data is heterogeneous and nonstandard—it includes particular geometrical characteristics and tacit knowledge like temporal changes in the built environment. As a result, it is challenging to employ heritage data in conservation actions in a straightforward manner. To address these issues, this research focuses on a data-driven approach to digital heritage management methods, from collecting raw data to the decision-making process, and offers a method curated with HBIM.

The research results were integrated into a multi-dimensional database, and information on the Heroon remains was managed with transparent case analyses. For instance, as Figure 16 illustrates, the programming architecture, from mapping to the 3D database, comprised an HBIM approach which enabled semantic geometric modelling of each free-standing stone at the site. This procedure also embodied the in-situ remains, since the modelling typology and metadata were created in a similar method. The colour coding of the visual programming language, generated in Revit's built-in Dynamo software, corresponds to the original inputs in the database. As the illustration indicates, the architecture of the algorithm inside the BIM environment was coherent with the preliminary inventory sheets.

The data-driven conservation actions were conducted in four modules: (i) data acquisition, (ii) data processing, (iii) information management, and (iv) curation (Fig. 17).

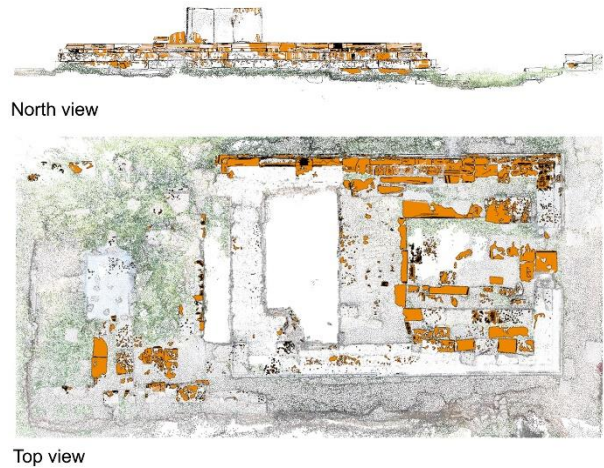


Figure 13: Lichen map of Heroon.

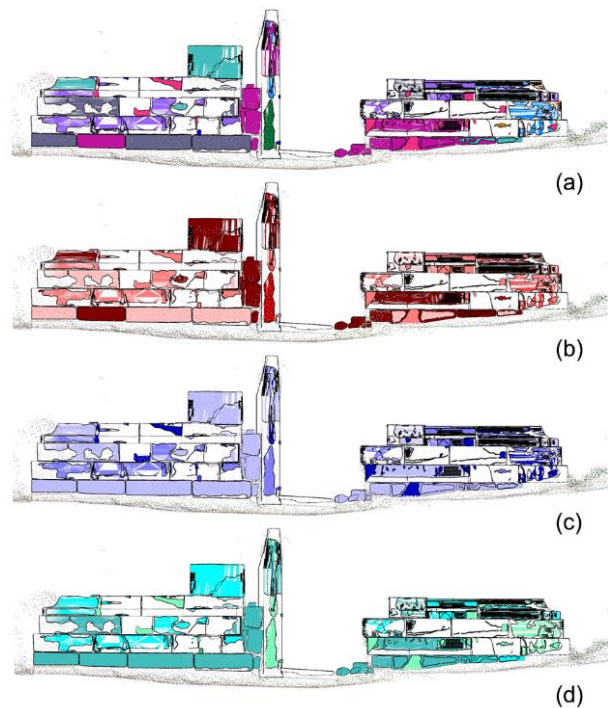


Figure 14: Intervention decisions for material deterioration: a) analysis; b) cleaning; c) consolidation; and d) maintenance steps.

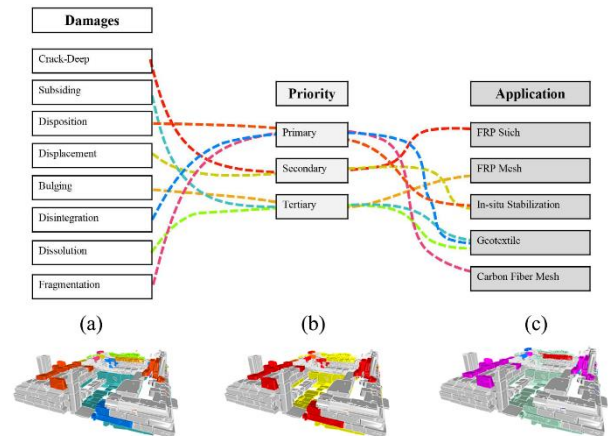


Figure 15: Intervention decisions linked to the 3D model: a) analysis; b) urgency level; and c) application method steps.

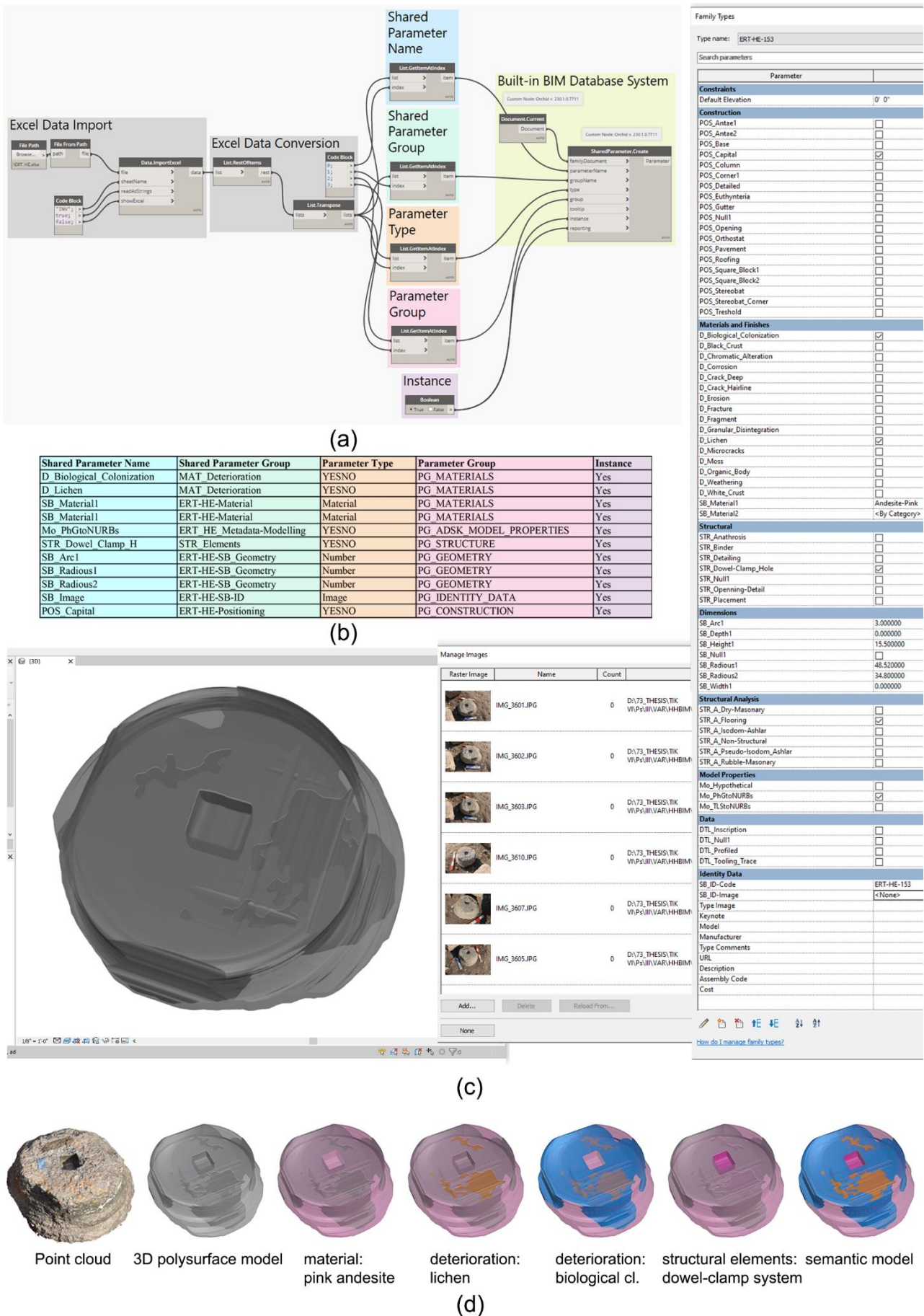


Figure 16: 3D database with colour-coded graphics: a) *Dynamo* data importing nodes; b) database metadata ready to import into BIM environment; c) parametric BIM element; and d) semantic geometric model of the stone (ERT-HE-153).

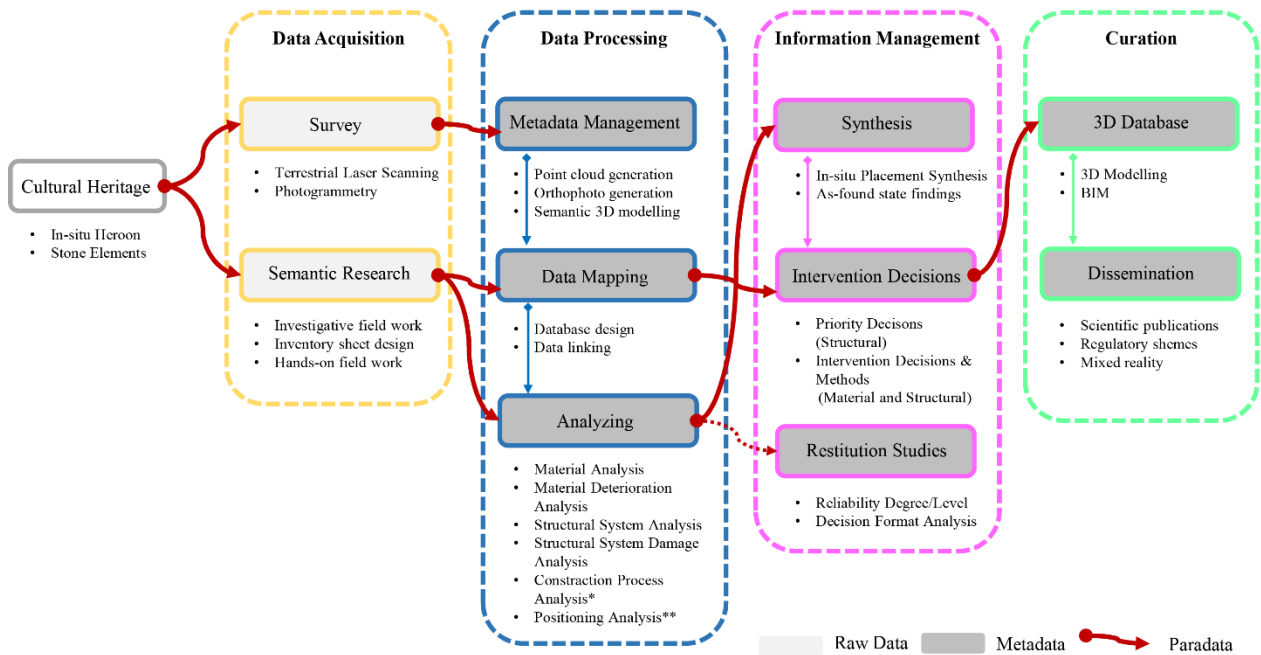


Figure 17: Data-driven conservation actions with *data-metamorphosis* interpretation.

The first module covered the survey of the Heroon remains and surrounding scattered stones by conducting TLS and digital photogrammetry. It also entailed on-site analytical interpretation, such as material culture analysis and archival research. The second module introduced data processing and involved the creation of digital references such as 3D point clouds, metadata generation, and database building. In the third module, the generated data was synthesized on the basis of the heritage domain's conservation action criteria. In the last module, curation, the HBIM environment enabled fully functional and high-fidelity management in 3D.

The method offered in this paper corresponds to both the digital heritage paradigm and the conservation sphere of heritage architecture by introducing modules which correspond to practice in the field. Theoretically, it adopts the resolutions contained in the relevant international charters and principles, particularly the London Charter (2009), the Seville Principles (2011), and the representation guidelines of ICOMOS, the International Council on Monuments and Sites (1990, 2003). It utilizes state-of-the-art digital methods, from surveys to simulations.

Consequently, it explores the link between the representation of heritage information and conservation by conducting an HBIM approach at an archaeological site. It looks at how the conservation process could be fully integrated into HBIM, covering both high levels of geometric accuracy and multi-level data related to conservation actions in a sophisticated manner.

There were many challenges when designing the method, despite the novel findings. First and foremost, the BIM software is still not directly operable from the initial 3D surveying to the processing of point clouds. Even though high accuracy was achieved in data acquisition, a large (semi-) manual effort was still required to segment, align, and convert point clouds into 3D models. These drawbacks make the process somewhat cumbersome and challenging for archaeological heritage sites, since these sites do not

necessarily have orthogonal geometrical forms and tangible information. In this paper, we tackled these issues by employing a semi-automated reverse engineering method which used NURBS-based geometric modelling software and parametric visual programming. Secondly, HBIM is still in its infancy because of its reliance on the built-in systems of BIM software. BIM software can neither operate various geometries directly nor handle complex heritage terminology and architectural information that differs from contemporary terminology and information. This means that BIM software is not fully capable of detecting the spatiality of heritage places without the integration of programming levels and migration to other platforms. For instance, this was an issue for the stone elements, since no masonry element category in the BIM software could represent the individual stones forming the wall. We built a new family in Revit using Dynamo, as a general model element rather than an available structural building element. In addition to the graphical disadvantages of BIM platforms, tacit and intangible heritage knowledge is not directly adaptable within them. An HBIM is not an imported historical 3D model of an asset. So far, BIM platforms present some problems in terms of heritage authenticity. Nevertheless, overall integration successfully enhances the BIM environment and provides a conservation action management tool with tailored workflows.

6. Conclusions and future trends

With the recent advances in geometric modelling and BIM, the cultural heritage field has become better equipped to digitally store, generate, and represent multiple data and information formats, and heritage condition monitoring has become more sophisticated. The tools are relatively beneficial for the digital reconstruction or design of buildings with highly accurate 3D surveying methods and allow the creation of “digital twins” of heritage sites.

Recently, the multi-dimensionality of the “digital twins” of heritage sites has come to a focal point: possible cost-effective and preventative conservation actions can be simulated before conducting them in real-time. Integrating tangible and intangible heritage knowledge and making tacit archaeological knowledge explicit, such as by documenting the decision-making process (paradata), provides more democratic heritage data. Future-proof workflows and comprehensive data management provide for sustainable dataflows, for instance, importing anachronical lab results and reports of deterioration and material typology and having respective decisions accordingly.

Despite the promise of NURBS-based modelling, which allows digital information and heritage knowledge to be interoperable and compatible regardless of the commercial or open-source software used, it is much trickier for archaeological heritage. The main reason for this is that BIM has been designed for buildings that do not exist or have already been designed with digital tools. Therefore, it is worth mentioning that not every heritage-related BIM environment is considered an HBIM

product. However, with interdependent information captured and generated with digital tools and a visually represented database, data-driven conservation actions can still be implemented in HBIM environments. Using both the accuracy of the geometric model, based on the 3D capture capacity, and NURBS-based modelling power, the data-driven process can be systemised and stored, and further management and monitoring of heritage sites can be realised.

Acknowledgements

The authors would like to express their sincere gratitude to the Erythrae archaeological site director Dr Ayşe Gül Akalın, for guaranteeing access to the archives and permission to study the Heron remains at Erythrae.

T.S. processed and performed the experiment, the analysis, and the research. G.S. contributed to the design of the study and advised the project. T.S. drafted the manuscript and designed the figures in consultation with G.S., who provided critical feedback and helped shape the manuscript.

References

- Achille, C., Lombardini, N., & Tommasi, C. (2015). BIM and cultural heritage: compatibility tests in an archaeological site. *Building Information Modelling (BIM) in Design, Construction and Operations*, 1, 593–604. <https://doi.org/10.2495/bim150481>
- Andronikos, M. (1980). “The Royal Tombs at Vergina” The Search for Alexander. *The Royal Graves at Vergina*, 26(5).
- Angulo, R., Pinto, F., Rodríguez, J., & Palomino, A. (2017). Digital anastylosis of the remains of a portal by master builder Hernán Ruiz: knowledge strategies, methods and modeling results. *Digital Applications in Archaeology and Cultural Heritage*, 7, 32–41. <https://doi.org/10.1016/j.daach.2017.09.003>
- Azhar, S. (2011). Building Information Modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, 11(3), 241–252. [https://doi.org/10.1061/\(ASCE\)LM.1943-5630.0000127](https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127)
- Bagnolo, V., Argiolas, R., & Cuccu, A. (2019). HBIM for archaeological sites: From SFM based survey to algorithmic modeling. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W9). <https://doi.org/10.5194/isprs-archives-XLII-2-W9-57-2019>
- Baik, A., Alitany, A., Boehm, J., & Robson, S. (2014). Jeddah historical building information modeling “JHBIM”-object library. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), 41–47. <https://doi.org/10.5194/isprsannals-II-5-41-2014>
- Baker, D. (2012). Defining paradata in heritage visualization. In A. Bentkowska-Kafel, H. Denard, & D. Baker (Eds.), *Paradata and Transparency in Virtual Heritage* (pp. 163–175). Ashgate.
- Banfi, F. (2016). Building information modeling – a novel parametric modeling approach based on 3D surveys of historic architecture. In M. Ioannides, E. Fink, A. Moropoulou, M. Hagedorn-Saupe, A. Fresca, G. Liestøl, ... P. Grussenmeyer (Eds.), *Digital Heritage Progress in Cultural Heritage: Documentation, Preservation, and Protection* (pp. 116–127). Cham: Springer International Publishing. <https://doi.org/10.1007/978-3-319-48496-9>
- Banfi, F. (2019). The integration of a scan-to-HBIM process in BIM application: the development of an add-in to guide users in Autodesk Revit. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W11), 141–148. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-141-2019>
- Banfi, F., Brumana, R., Landi, A. G., Previtali, M., Roncoroni, F., & Stanga, C. (2022). Building archaeology informative modeling turned into 3D volume stratigraphy and extended reality time-lapse communication. *Virtual Archaeology Review*, 13(26), 1–21. <https://doi.org/10.4995/var.2022.15313>
- Banfi, F., Fai, S., & Brumana, R. (2017). BIM Automation: advanced modeling generative process for complex structures. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 4(2/W2), 9–16. <https://doi.org/10.5194/isprs-annals-IV-2-W2-9-2017>
- Banfi, F. (2020). HBIM, 3D drawing and virtual reality for archaeological sites and ancient ruins. *Virtual Archaeology Review*, 11(23), 16–33. <https://doi.org/10.4995/var.2020.12416>

- Banfi, F. (2021). The evolution of interactivity, immersion and interoperability in HBIM: Digital model uses, VR and AR for built cultural heritage. *ISPRS International Journal of Geo-Information*, 10(10). <https://doi.org/10.3390/ijgi10100685>
- Barazzetti, L., Banfi, F., Brumana, R., & Previtali, M. (2015). Creation of Parametric BIM Objects from Point Clouds Using Nurbs. *Photogrammetric Record*, 30(152), 339–362. <https://doi.org/10.1111/phor.12122>
- Barazzetti, L. (2016). Parametric as-built model generation of complex shapes from point clouds. *Advanced Engineering Informatics*, 30(3), 298–311. <https://doi.org/10.1016/j.aei.2016.03.005>
- Bassier, M., Hadjidemetriou, G., Vergauwen, M., Van Roy, N., & Verstryngne, E. (2016). Implementation of scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures. *Lecture Notes in Computer Science*, 10058. https://doi.org/10.1007/978-3-319-48496-9_7
- Bosco, A., D'Andrea, A., Nuzzolo, M., & Zanfagna, P. (2019). A BIM approach for the analysis of an archaeological monument. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W9), 165–172. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-165-2019>
- Brumana, R., Della Torre, S., Previtali, M., Barazzetti, L., Cantini, L., Oreni, D., & Banfi, F. (2018). Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention—the Basilica di Collemaggio (L'Aquila). *Applied Geomatics*, 10(4), 545–567. <https://doi.org/10.1007/s12518-018-0233-3>
- Brumana, R., Della Torre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., ... Banfi, F. (2017). HBIM challenge among the paradigm of complexity, tools and preservation: The Basilica di Collemaggio 8 years after the earthquake (L'Aquila). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W5), 97–104. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-97-2017>
- Brumana, R., Oreni, D., Barazzetti, L., Cuca, B., Previtali, M., & Banfi, F. (2020). Survey and scan to BIM model for the knowledge of built heritage and the management of conservation activities. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Digital Transformation of the Design, Construction and Management Processes of the Built Environment. Research for Development* (pp. 391–400). Cham: Springer. https://doi.org/10.1007/978-3-030-33570-0_35
- Capone, M., & Lanzara, E. (2019). Scan-to-BIM vs 3D ideal model HBIM: parametric tools to study domes geometry. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W9), 219–226. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-219-2019>
- Castellano-Román, M., & Pinto-Puerto, F. (2019). Dimensions and levels of knowledge in heritage building information modelling, HBIM: the model of the charterhouse of Jerez (Cádiz, Spain). *Digital Applications in Archaeology and Cultural Heritage*, 14, e00110. <https://doi.org/10.1016/j.daach.2019.e00110>
- Chiabrande, F., Lo Turco, M., & Rinaudo, F. (2017). Modeling the decay in an HBIM starting from 3D point clouds. A followed approach for cultural heritage knowledge. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W5), 605–612. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-605-2017>
- Engelmann, H., & Merkelbach, R. (1972). *Die Inschriften von Erythrai und Klazomenai*. Bonn: R.Habelt.
- Fredheim, L. H., & Khalaf, M. (2016). The significance of values: heritage value typologies re-examined. *International Journal of Heritage Studies*, 22(6), 466–481. <https://doi.org/10.1080/13527258.2016.1171247>
- Garagnani, S., Gaucci, A., & Gruška, B. (2016). From the archaeological record to archaeobim: the case study of the Etruscan temple of Uni in Marzabotto. *Virtual Archaeology Review*, 7(15), 77–86. <https://doi.org/10.4995/var.2016.5846>
- ICOMOS. (1990). Charter for The Protection and Management of The Archaeological Heritage. Retrieved February 21, 2021, from International Committee for the Management of Archaeological Heritage (ICAHM) website: https://www.icomos.org/images/DOCUMENTS/Charters/arch_e.pdf
- ICOMOS. (2003). Principles for The Analysis, Conservation and Structural Restoration of Architectural Heritage. Retrieved February 21, 2021, from International Council on Monuments and Sites website: https://www.icomos.org/charters/structures_e.pdf
- Jouan, P., & Hallot, P. (2019). Digital twin: a HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W15), 609–615. <https://doi.org/10.5194/isprs-archives-XLII-2-W15-609-2019>
- Lee, J., Kim, J., Ahn, J., & Woo, W. (2019). Context-aware risk management for architectural heritage using historic building information modeling and virtual reality. *Journal of Cultural Heritage*, 38, 242–252. <https://doi.org/10.1016/j.culher.2018.12.010>

- London Charter. (2009). The London charter for the use of 3-dimensional visualization in the research and communication of cultural heritage. Retrieved February 20, 2022, from http://www.londoncharter.org/fileadmin/templates/main/docs/london_charter_1_1_en.pdf
- Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, 27(4), 311–327.
- Rabbani, T., van den Heuvel, F., & Vosselman, G. (2006). Segmentation of point clouds using smoothness constraint. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(5), 248–253.
- Sarıcaoğlu, T., & Köşklük Kaya, N. (2020). As-Built Environment Paradata Model Utilized by hBIM. In D. Engin & E. Kızılörenli (Eds.), *International Symposium: Architecture, Technology and Innovation* (pp. 352–358). İzmir: Yaşar Üniversitesi.
- Sarıcaoğlu, T., & Köşklük Kaya, N. (2021). A combined use of image and range-based data acquisition for the three-dimensional information mapping archaeological heritage. *Mersin Photogrammetry Journal*, 3(1), 1–9.
- Sayão, L. (2016). Digitization of cultural collections: reuse, curation and preservation. *IV Seminário Serviços de Informação em Museus*, 245–258.
- Stanish, C. S., & Levy, T. E. (2013). Cyber-archaeology and world cultural heritage: insights from the holy land. *Bulletin of the American Academy of Arts and Sciences*, 66, 26–33. Retrieved from <https://www.amacad.org/news/cyber-archaeology-and-world-cultural-heritage-insights-holy-land>
- Sun, Z., & Zhang, Y. (2018). Using drones and 3D modeling to survey Tibetan architectural heritage: A case study with the multi-door stupa. *Sustainability*, 10(7). <https://doi.org/10.3390/su10072259>
- Sztwiertnia, D., Ochałek, A., Tama, A., & Lewińska, P. (2019). HBIM (Heritage Building Information Model) of the Wang Stave Church in Karpacz—case study. *International Journal of Architectural Heritage*, 15(5), 713–727. <https://www.tandfonline.com/doi/full/10.1080/15583058.2019.1645238>
- Tammaro, A. M. (2016). Heritage curation in the digital age: professional challenges and opportunities. *International Information & Library Review*, 48(2), 122–128. <https://doi.org/10.1080/10572317.2016.1176454>
- Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques. *Automation in Construction*, 19(7), 829–843. <https://doi.org/10.1016/j.autcon.2010.06.007>
- The Seville Principles. (2011). International Principles of Virtual Archaeology The Seville Principles. Retrieved May 2, 2019, from <http://smartheritage.com/seville-principles/seville-principles>
- Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38, 109–127. <https://doi.org/10.1016/j.autcon.2013.10.023>