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ICT BASED STRATIGRAPHY FOR ARCHITECTURAL HERITAGE: TOWARDS DIGITAL MODELS SUPPORTING THE INVESTIGATIVE PROCESS

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Abstract

Architectural stratification is the embodiment of the morphogenetic process of historic buildings. Understanding this complex configuration composed of elements unevenly distributed in space, offers insights into the construction history and structural behaviour of buildings. The conventional stratigraphic approach relies heavily on visual inspection, manual mapping, and the highly schematic Harris Matrix. in addition to being laborious and time-consuming, it often leads to poor assessments or omissions, particularly in densely stratified or hard-to-access areas. Despite the emergence of innovative procedures for exploring diachronic and multidisciplinary datasets, such initiatives remain sporadic and have yet to produce a systemic update of the overall workflow. Within this framework, the present study proposes a stratigraphic workflow grounded in recent ICT advancements, demonstrating their added value and reliability for both investigation and interventions processes.

Keywords

ICT, InfoVis, reality-capture, computer vision, building stratigraphy, 3D models

1. *Introduction*

The attention paid to the vestiges of ancient civilizations is as old as the sedentarization of men. Whether for the reuse of materials and land, the looting of antiquities or as a source of ancestral and cultural knowledge, artifacts bequeathed throughout history have always been subject to recovery.

The architectural and constructive stratification is the embodiment of the diachronic and evolutionary history of built environment. A stratified construction is therefore considered as a diachronic entity, composed of the overlap of successive synchronic construction units, linked by spatial and temporal relationships. Physically, the stratification appears in several forms and at different scales. It could be materialised as a multiplicity of construction materials within the same built environment, diversity of technical and stylistic expressions, or coexistence and superposition of architectural and urban spaces.

Stratification has consistently occupied a central place in the theoretical discourse on conservation and restoration. Viollet-le-Duc, an emblematic figure of restoration in the 19th century, highlighted the evolutionary and diachronic nature of medieval buildings, emphasising the successive changes that had shaped them over time (Viollet-le-Duc, 1854). Since the latter half of the 20th century, the field of heritage conservation has progressively expanded on a global scale, largely driven by the initiatives of the International Council on Monuments and Sites "ICOMOS". This evolution brought the historical dimension of heritage assets to the forefront of international discourse. During the Second International Congress of Architects and Technicians of Historic Monuments organised in Venice, in 1964, the diversity of constructive, stylistic, and technical layers in historic buildings was acknowledged as an inherent characteristic to be respected and valued (ICOMOS, 1964). This perspective has been consistently reaffirmed through ICOMOS-led conferences and commissions, and further consolidated by a series of key publications—including, but not limited to, the Nara Document on Authenticity (ICOMOS, 1994), the ICOMOS Ename Charter (ICOMOS, 2008), and the Valletta Principles (ICOMOS, 2011).

Originally developed in the field of geology, stratigraphy as a scientific study of the component layers of the Earth's crust was introduced into archaeology to investigate sites stratification, and subsequently adopted to the field of archaeology of architecture in the 1970's (Tirello & Vilella, 2015).

Mainly used for excavation tasks, Harris method, considered as the current state of the art in archaeological stratigraphy, is used for recording strata identified during the diggings in their relative succession order (May et al., 2023). According to this method, both manufactured and sedimentary layers are recorded in reverse order of their deposition. Each homogeneous stratum is bounded by interfaces, and considered a stratigraphic unit "SU", that serves as the fundamental building block for recording stratigraphic sequences (Harris, 1979). These sequences are represented graphically in an acyclic diagram known as the Harris Matrix, which represents the SUs and stratigraphic relationships respectively with nodes and edges. The nodes are arranged vertically from oldest to most recent, while the edges point upwards to indicate posterior relationships or horizontally to indicate contemporaneous relationships (Harris, 1979).

It is important to note that the organization of SUs within the Harris Matrix is based solely on their depositional positions , without taking into consideration their content (Traxler & Neubauer, 2009). However, such analytical data may be integrated during post-excavation analysis to highlight specific patterns or clusters based on the matrix (Discamps et al., 2023; Roskams, 2020).

Although Harris' stratigraphic method was originally developed for the pre-analytical recording and schematic reconstruction of excavated volumes, it has been directly applied to the study of architectural heritage from the 1970s by architects working on restoration and historical monuments (Genovez, 2012). In this context, it was used to interpret building stratification without substantial adaptation to the objectives and specificities of architectural logic. Practical experience has nonetheless revealed certain limitations of this approach within professional practice.

In this paper, we propose an ad hoc workflow for the study of architectural stratification, leveraging the affordances of reality capture technologies and information visualization (InfoVis) tools to enable optimal data utilization and deeper insight generation. We explore the potential of as-found 3D models as a foundational framework for the inspection and extraction of stratigraphic data laying on available technologies. Then, we propose an alternative to the conventional Harris Matrix, to visualise both quantified and relative chronologies, and to support interpretations of the processes and causalities underlying architectural transformations. Finally, we present the use of tailored interactive and multimodal visualization tools designed to represent simultaneously spatial, morphological, and temporal dimensions—enhancing the display of the artifact's morphogenesis over time.

Since our goal is to propose a methodological workflow for retracing the architectural stratification process in its multidimensionality, the Sufi lodge of Sidi Rached, located in the historic city of Constantine (Algeria), was selected as a case study to evaluate the effectiveness of the proposed approach. The building was chosen for its pronounced stratification, clearly legible across its façades in both construction techniques and stylistic features. These visible heterogeneities reflect successive functional and structural transformations over time, making the site particularly suitable for testing the robustness and integrative capacity of the workflow.

The following section reviews the use of the stratigraphic method in architecture, along with the various developments and improvements introduced in this context. Section 3 presents the workflow developed in response to the shortcomings identified previously, beginning with a general overview of the methodological process and followed by its detailed application to the selected case study. Section 4 reports the results of this application, while Section 5 discusses its contributions and limitations. Finally, Section 6 outlines the main conclusions and future research directions.

2. *Review of the Use and the evolution of the Harris stratigraphic method*

2.1 Vertical Stratigraphy: An Archaeological Methodology

Harris' stratigraphic method has been widely employed in the study of historical buildings, particularly during the analysis and knowledge production phase. It involves collecting construction traces inscribed on the surfaces of structures, which reveal their chronologic and evolutionary histories. This method has been especially useful for analysing poorly documented artifacts, and was introduced for the study of built heritage by architects involved in architectural restoration and "Archeologia dell'Architettura", including Parenti, Doglioni, and Mannoni (Genovez, 2012).

Given the primacy of morphological and spatial data in architecture, the identification of interfaces and stratigraphic building units "SBU" is carried out in situ by trained conservation practitioners through visual inspection, involving a careful examination of surface features. Technical guidelines have been developed to support and supervise these tasks (Uk Icomos, 1990). The documentation of the stratigraphic components proceeded in three stages: 1) on two-dimensional drawings —plans, sections, and elevations—used to represent SBUs and contact interfaces through colour codification and numerical identifiers; 2) the recording of findings and the contents of each SBU in "single context recording" sheets, for post-excavation processing; 3) on directed acyclic diagrams -Harris Matrix- used to record SBUs through digital identifiers and their respective succession relationships (Desachy, 2008a).

Despite its widespread application, studies on the use of the Harris method (Haouacha, 2015) and critical assessments of archaeological stratigraphic analysis applied to historic buildings (Tirello & Vilella, 2015), have highlighted significant methodological challenges. Indeed, given the nature of the architectural fabric, the laws of archaeological stratigraphy as defined by Harris, prove to be inadequate to describe buildings stratification (Haouacha, Ravaglia, & Boufenara, 2025). In addition to being a non-destructive and analytical study, architectural stratigraphy does not conform to the rules of gravitational deposition underlying the four main laws of Harris. This is because architectural transformation processes rarely follow a strictly vertical order.

Furthermore, the objective of architectural stratigraphy extends beyond establishing a sequence of deposition. It seeks to understand the morphogenesis of buildings, describing processes of permanence and transformation (Dudek & Blaise, 2010), and to apprehend the morphological and structural relationships between SBUs, in order to preserve their materiality and inherent values. In this context, it has been shown that a chronological sequence derived solely from the relative topological relationships between layers, as represented by the Harris Matrix, is insufficient to fully grasp the evolution of historic buildings(Davies, 1987; Genovez, 2012). Beyond topological evidence, interdisciplinary data—contextual, semantic, and historical—must also be explored to reconstruct the construction genesis of artefacts. In this sense, it is no longer relative topological organization alone that forms the basis for semantic and genetic interpretation, but rather a continuous interplay between interdisciplinary information and topological configuration that guides chronological sequencing.

Moreover, the Harris Matrix does not account for quantified chronology, such as intervals of permanence or the coexistence of various building phases, nor does it reveal transitional spots between different states of transformation (Neubauer et al., 2018). In cases of densely stratified architectural ensembles, the Harris Matrix often becomes difficult to decipher and interpret (LAYT & Recording Archaeology, 2016).

From a graphical point of view, although Harris method was developed with the establishment of open areas framework, it is commonly based on the accumulation of two-dimensional plans, elevations and sections, to graphically identify and record SBUs. In architecture, it is fundamental to deal with the three-dimensionality which characterises the evolution of spaces and volumes (Campisi et al., 2019).

2.2 Digitally assisted stratigraphy

2.2.1 The chronological level

With the expansion of the use of the Harris method, interest has been focused on editing the Harris diagram, particularly when managing data from highly stratified sites and building sets. In this perspective, work was undertaken in the late 2000s to computerise and automate the generation and the compilation of the Harris Matrix for practical and systematic use.

The work carried out by Traxler and Neubauer (2009) focused on developing an intuitive and interactive graphical user interface, implemented in accordance with Harris's principles of archaeological stratigraphy and tailored to user needs. The tool enables the structured organization of in situ data, allowing for seamless navigation and efficient compilation of the various components of the stratigraphic matrix. The initial model, which primarily supported the representation of relative chronological relationships, was later expanded to incorporate temporal relationships based on intervals (Neubauer et al., 2018). This enhancement facilitated the integration of the results from post-excavation analyses of the recorded SUs, thereby supporting the construction of their relative chronologies and their placement within the corresponding temporal and historical fields.

In the same vein, several research works were dedicated to the integration of paradata (May et al., 2023), and interpretations generated from the post-excavation analysis into the Harris Matrix in the form of clustering(Campisi et al., 2019), representing phases and periods (May, 2020). In addition to organising the matrix by stages and levels, Desachy (2008b) addressed the issue of uncertainty and incorporated quantified time using an interval chart. This chart relies on *terminus post quem* (TPQ) *and terminus ante quem* (TAQ) indicators for each stratigraphic unit, in line with Harris's principles of superposition and stratigraphic succession.

Some researchers have adapted the Harris diagram to better suit the specific goals of stratigraphic studies for architectural assets.

Demetrescu (2015) used the Harris stratigraphic approach as a foundation to support the virtual (hypothetical) reconstruction of past states of historic buildings. He proposed extending the Harris Matrix by defining and integrating new stratigraphic entities as additional concepts and nodes. This version of the matrix enables the management and representation of the processes underlying scientific potential reconstructions, by incorporating speculative components alongside the existing stratigraphic elements (Demetrescu, 2018).

Along the same line, Villalobos (2024) restructured the diagram as a methodological tool for documenting construction components in the context of conservation planning. He introduced new variables based on the idea that architectural elements serve as the fundamental units of stratification. This led to the definition of three specialised nodes: (1) structural stratigraphic units, (2) decorative stratigraphic units, and (3) pathology stratigraphic units. These nodes were represented using a customised codification system—node shapes and edge configurations. Furthermore, the standard Harris relationships were replaced with connections tailored to building contexts, such as "covered by", "cuts to", "attached to", or "carried by".

Beyond the level of information integrated into stratigraphic sequencing and the reliability of chronological schematization, the spatial representation and exploration of morphological data remain the major concern in built heritage studies, given that the spatiality and geometrical information of buildings is the principal object of study in architecture.

2.2.2 The geometric and spatial level

As regards spatial and morphological data, the issue of collecting and graphically representing stratigraphic data based on two-dimensional drawings has been widely discussed. Actually, with the evolution of Remote sensing technologies, and their broader use in the field of architecture and built heritage, many works highlighted the considerable contribution of these technologies to the stratigraphic analysis. Aiello et al (2014) emphasised the role of photogrammetry-based models to improve the stratigraphic analysis allowing generating more accurate and detailed two-dimensional drawings for mapping interfaces and -previously identified- units of stratification. Conversely, several other research has focused on the use of reality-based models to generate accurate textured orthophotos, which serve as a basis for labelling the stratigraphic data, derived from prior analysis (Trizio et al., 2022).

The evolution of the use of BIM technologies applied to heritage assets in the last decade has led to significant methodological advances in the surveying of multi-layered heritage structures. The adoption of HBIM models was particularly motivated by their ability to integrate both geometrical and non-geometrical data within a single digital mock-up, effectively organising the large volume of gathered information around a spatial model. However, several challenges have hindered the widespread adoption of BIM technologies for heritage applications, notably the inadequacy of parametric models to accurately represent the complexity and singularities of historical building shapes and elements, as well as the demanding task of data enrichment. Various experiments have been developed in the literature to address these limitations. For the creation of as-found HBIM models, a scan-to-BIM procedure is generally employed to produce optimally accurate models (Diara & Rinaudo, 2020; Galera-Rodríguez et al., 2022). Regarding the semantic enrichment of the model, it is typically achieved through the creation and assignment of attributes using shared parameters (Brusaporci et al., 2018). Santoni et al (2021) proposed an innovative strategy for modelling an accurate parametric model using a hybrid approach that combines terrestrial laser scanning and photogrammetry-based point clouds, meshes and NURBs, along with 2D drawings. The modelling process was performed on Revit, and was supported by both Autodesk families and external families. The semantic structuring of the model was based on a classification derived from "Archeologia dell'Architettura" classical methodologies. Information was organised into tables and connected via external links. Finally, the HBIM model enabled the execution of cross-queries using Dynamo for Revit, which allows for the creation of customised applications using a Visual Programming Language. Similarly, Banfi (2021) explored various applications of BIM in the heritage field, emphasising the diversity of modelling approaches and information enrichment methods tailored to specific objectives. His presentation of the stratigraphic study of Masegra Castle highlighted the complexity of the task of mapping interfaces and stratigraphic building units, as well as the significant costs involved in terms of time and computational resources.

Thus, while HBIM has proven effective in integrating heterogeneous data and enhancing sharing and interoperability, its contribution remains limited to the representation and mapping of analytical results produced in parallel, —often derived from traditional investigation methods— such as stratigraphic inspection, direct visual assessment of surfaces, and secondary data-sources like archives and documentation. Moreover, despite the ingenious and tedious modelling techniques, the resulting models tend to remain relatively simplified when compared to the inherent complexity of built heritage structures.

Building upon the innovations and limitations discussed above, the following section introduces the proposed methodological framework. Specifically, we present a comprehensive workflow that redesigns the stratigraphic process through the integration and interoperability of multiple procedures —building on recent advancements in the field of building heritage analysis— within a single coherent framework. This approach aims to establish a more systematic, reproducible, and operational method for stratigraphic interpretation.

3. *Material and methods*

Our research is grounded in the consideration that stratification constitutes a diachronic process generating a multilayered morphology composed of stratigraphic building units "*SBUs*" assembled multidirectionally, and interconnected through both topological and chronological relationships. These relationships become intelligible through the identification of *SBU*s boundaries, their respective spatial locations, as well as their positional and historical trajectories.

Based on this conception, we adopted a multi-level mereological approach enabling the simultaneous investigation of the spatial, morphological, and chronological dimensions of architectural stratification.

- At the spatial level, we propose the use of high-precision 3D models as the basis for analysing the distribution of stratigraphic and temporal units. This approach allows the transition from visual inspection to more controlled, multi-scale, desk-based analysis, and from cumulative sectional views to a unified, holistic model of the architectural structure. This can be realised through the acquisition of precise and detailed spatial data through reality capture techniques, enabling multi-scale reading and processing.
- At the morphological level, the acquired 3D model is processed to establish the building's composition, highlight the topological and formal relationships between SBUs, and identify their causal interdependencies. At this stage, we propose the use of 3D segmentation and classification techniques—partitioning the 3D model into homogeneous regions based on shared properties, and subsequently aggregating them into class clusters—resulting in the development of thematic mappings of the identified stratigraphic entities (Grilli, Dininno, Marsicano, et al., 2018; Nguyen & Le, 2013).
- At the chronological and temporal level, we aim to trace the historical evolution of the artifact by identifying continuities, key transformation phases, and the duration of characteristic periods. For this purpose, we suggest using sequential representations of historical data through timelines. Simultaneously, we enable the spatial visualization of chronological organization and stratigraphic genesis throughout the artifact's life cycle by spatializing and annotating the previously acquired 3D model, assigning a semantic category or identifier to each segmented region.(Manuel et al., 2014; Croce et al., 2020).

Finally, with the aim of establishing a systemic correlation between the spatio-morphological and chronological levels, we structure the workflow as an integrated information system designed to organise and articulate data, tools, and processes within a shared environment (Figure 1). This structuring allows us to optimise the use of available resources and to ensure the production, management, visualization, and sharing of information, thereby supporting a comprehensive and holistic understanding of multilayered artifacts.

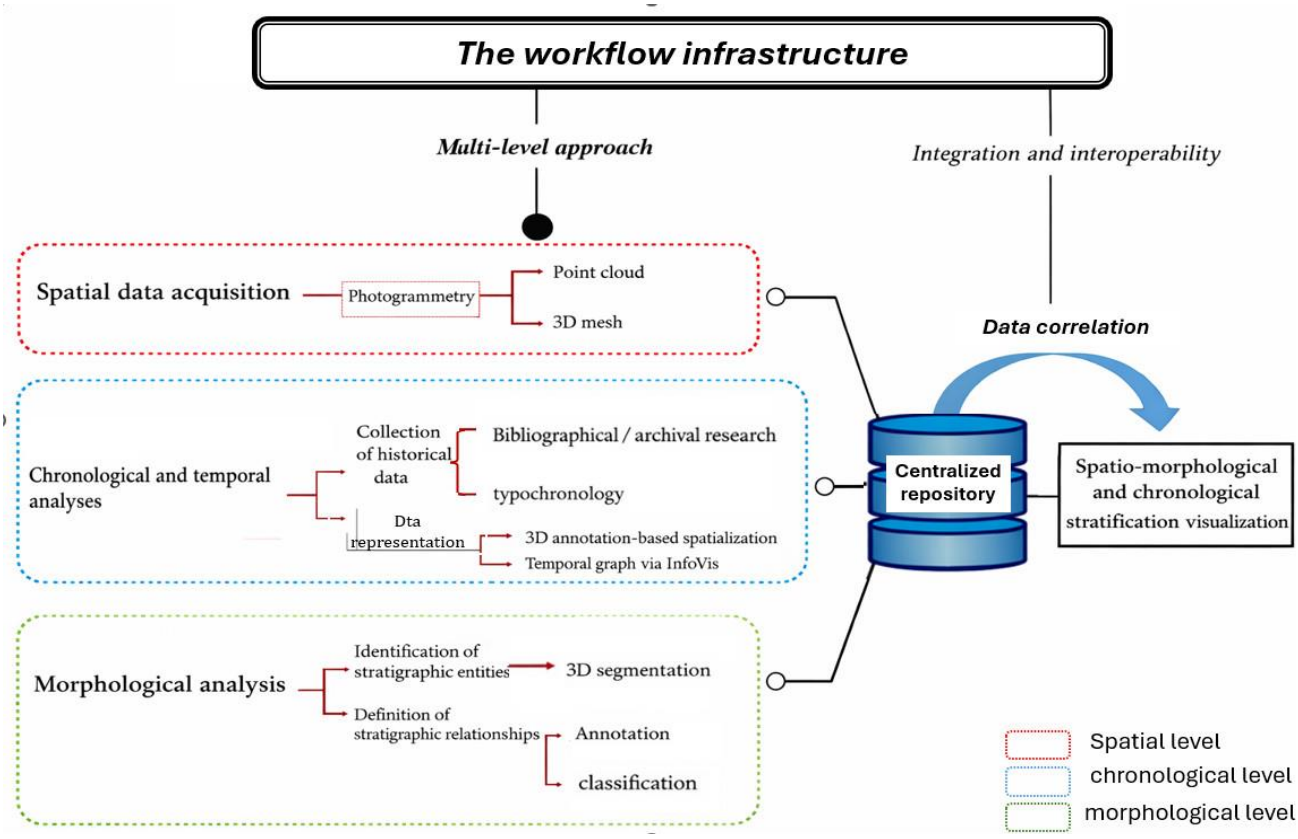

Fig.1: The proposed methodological workflow for architectural stratigraphy

To demonstrate the practical implementation of the proposed workflow, we conducted an experimental application on a selected historical building. The chosen case study was the Sufi lodge of Sidi Rached, located on the edge of the Rhumel canyon in Constantine (Figure 2). This building was selected due to its pronounced stratification, which is clearly legible across its various façades in both construction techniques and stylistic features. These visible heterogeneities reflect successive functional and structural transformations that have occurred over time, making the site particularly suitable for testing the methodological robustness and integrative capacity of the proposed workflow.

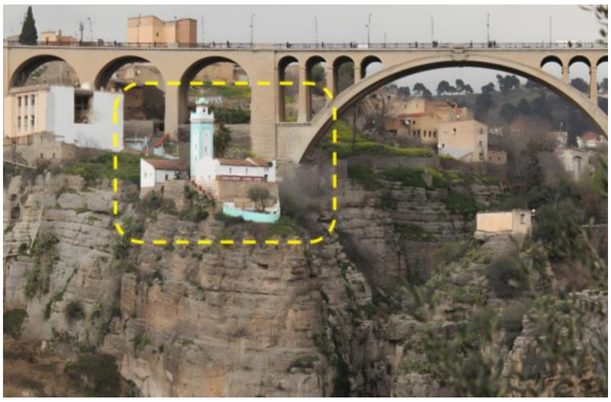

Fig. 2: The Sufi lodge of Sidi-Rached (source: the author. 2023)

3.1. The spatial level: Data acquisition and collection

Given the site's highly uneven topography, which complicated the use of terrestrial laser scanning, and the administrative restrictions on the use of UAVs, a terrestrial photogrammetric survey was carried out as the most appropriate method for acquiring spatial data.

For the digital reconstruction, a dataset of 300 photographs was captured from multiple viewpoints, covering the entire building. To ensure full record of the roof, images were taken from the bridge overlooking the structure. SfM-based photogrammetry procedure was performed using COLMAP and Meshroom (AliceVision) software applications. A dense point cloud and a triangular mesh were generated, enabling a complete and highly detailed reconstruction of masonry structure (Figure 3).

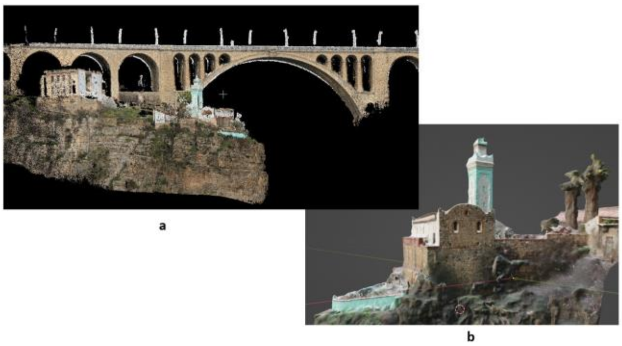

Fig. 3: The generated 3D models. a) Dense point-cloud, b) Triangular mesh

3.2. The morphological level: 3D models for investigating, identifying, and representing stratigraphic data

The primary task of a stratigraphic study is to identify the various SBUs or subsets that constitute a multi-layered building. This is typically achieved through a segmentation process, which relies on detecting interfaces marked by discontinuities in materials, forms, construction techniques, and structural or stylistic heterogeneity. To avoid misinterpretations—particularly in cases involving identical repairs, anastylosis, or advanced deterioration—documentary data must be considered in the identification of stratigraphic interfaces.

Traditionally, in the building archaeology method, SBUs were identified mainly through a classification task, based on the visual inspection of surfaces and building materials. This meticulous and time-consuming process had to be conducted in situ, relying heavily on the expertise and observational skills of surveyors, often under tight time constraints. The emergence of as-found digital models marks a shift on heritage analysis from physical to virtual fieldwork, enabling real-time accessibility and availability of data. These models enhance thorough inspection and diagnosis through controlled navigation and processing, making them especially valuable for inaccessible or hard-to-reach areas and densely stratified structures.

In this context, recent advances in computer vision have significantly improved the automated and semi-automated processing of 3D digital models, particularly in relation to data segmentation and classification (Abergel et al., 2023). Manuel et al (2014) proposed transferring manually labelled regions from images to their corresponding 3D generated point clouds, via a bijective relationship. Similarly, Pellis et al (2022) introduced a back-projection method that maps deep learning–based semantic segmentation from 2D images onto their associated 3D models. Building on these contributions, recent research has increasingly focused on integrating label transfer directly into the photogrammetric workflow, thereby laying the foundation for what is now known as semantic photogrammetry (Murtiyoso & Grussenmeyer, 2019; Stathopoulou & Remondino, 2019).

In a related effort, Vandenabeele et al (2023) employed convolutional neural networks (CNNs) on ortho-photos derived from SfM surveys to achieve individual brick segmentation in large-scale masonry.

Based on the progress made in this direction, we have mainly opted in our workflow for two semi-automatic segmentation methods, for the identification of SBUs, at different granularities. We first performed a texture-based segmentation, aiming to aggregate areas with a high degree of homogeneity. We adopted a reverse projection approach, as proposed by Grilli et al (2018). In this method, the original textured mesh is remeshed to simplify and refine its geometry, then unwrapped in Blender to produce a UV map. This UV map serves as the input for training a machine learning-based segmentation model using Fiji (ImageJ) and the Trainable Weka Segmentation plugin. The resulting labels are then assigned to the 3D model as a texture, using a mapping process. Figure 4 shows the segmentation workflow.

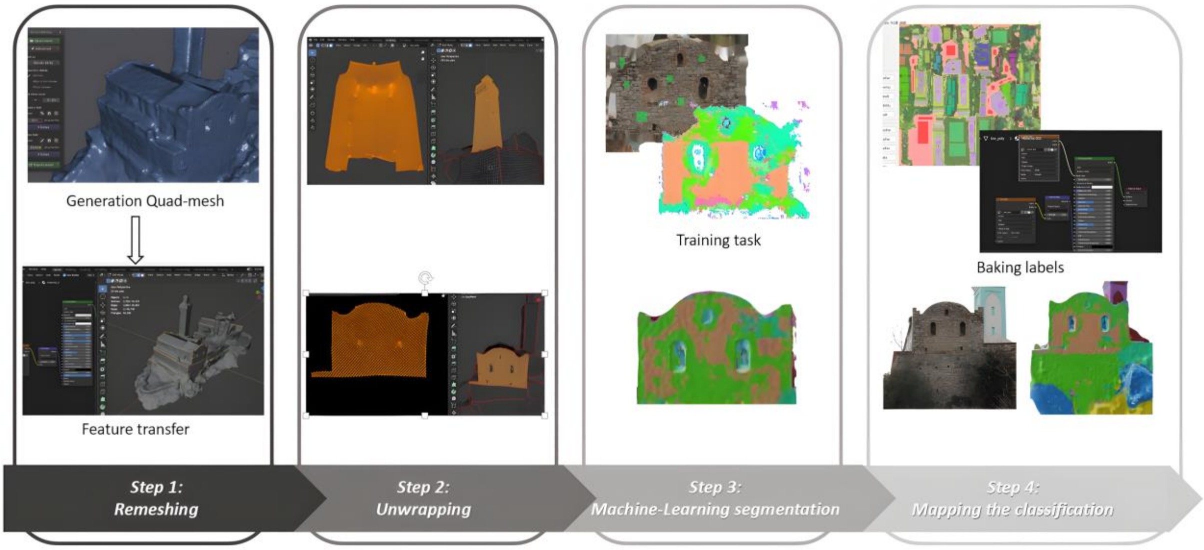

Fig. 4: Stratigraphic building units identification process through Machine-Learning segmentation

In addition to identifying homogeneous areas based on construction materials and textures, a second segmentation was performed -based on the geometric features- to detect repair areas and changes in construction techniques. For this, a stone-by-stone segmentation was applied, using the masonry segmentation plugin of CloudCompare, proposed by Forster et al (2023). This method consists of generating 2.5D orthogonal planar projection from the 3D model, and applying a 2D continuous Walvet transform to the depth map, for detecting and isolating the mortar, thus highlighting the shape and contours of individual stone blocks. Due to the irregularity in joint thickness and depth, coupled with the limited accuracy of the photogrammetric model in capturing joint details, the plugin's manual segmentation function was used to assist the automatic segmentation process. Figure 5 presents a sample illustration of the stone-by-stone segmentation process.

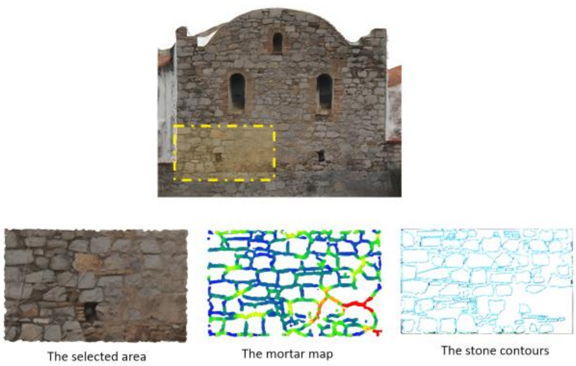

Fig. 5: Stone-by-stone semi-automatic segmentation

3.3. The Chronological level: Timelines for Representing Diachronicity

Regarding the collection of historical and chronological information, a wide array of graphic and textual sources was consulted and analysed, encompassing various phases in the artifact's existence. These included archival materials from the Ottoman and French colonial periods (Féraud, 1868), iconographic documents and ancient photographs (Honoré, 1910), research reports, maps and travel accounts from earlier times (Al-Bakrī, 1859; Al Idrīsī, 1250).

in addition to morphological genesis, the stratigraphic study of built heritage aims to grasp and represent spatio-temporal evolutions as indicators of the cultural value of the heritage assets, as well as a basis for intervention decision-making. Every single SBU must be thoroughly documented for the readability of the morphogenesis process in one hand, and for the analysis of mutual relationships and interactions between different parts of the building on the other hand. In this context, the integration of temporal, spatial and morphological data to the 3D model enhances our ability to interpret the building's evolution and organization. Numerous studies have already addressed the spatiality of historical data, notably through the creation of temporal thematic maps by the annotation of 3D models(Stefani, 2007). Building on this, the use of multi-layered annotations—combining stratigraphic material-based segmentation with temporal annotation—enables effective cross-referencing of information (Messaoudi et al., 2019;

Stefani et al., 2012) thereby improving interpretation and supporting inferences.

In parallel, Dudek and Blaise (2008) demonstrated that timelines can convey both quantitative data—such as absolute dates, durations, and intervals—and qualitative information, including the nature of changes, types of transformation, and underlying factors — through the integration of visual markers.

Building on this, the present work proposes an object-oriented-like graph as an alternative to the Harris Matrix, replacing its nodes with timelines—each representing an identified SBU and carrying specific attributes such as an ID, colour code, and start/end dates. These timelines are nested within broader temporal containers, referred to as chronological units (Haouacha et al., 2025) — which reflect varying levels of granularity depending on the scope of the study—activities, phases, or epochs. Figure 6 shows the proposed chronological graphic.

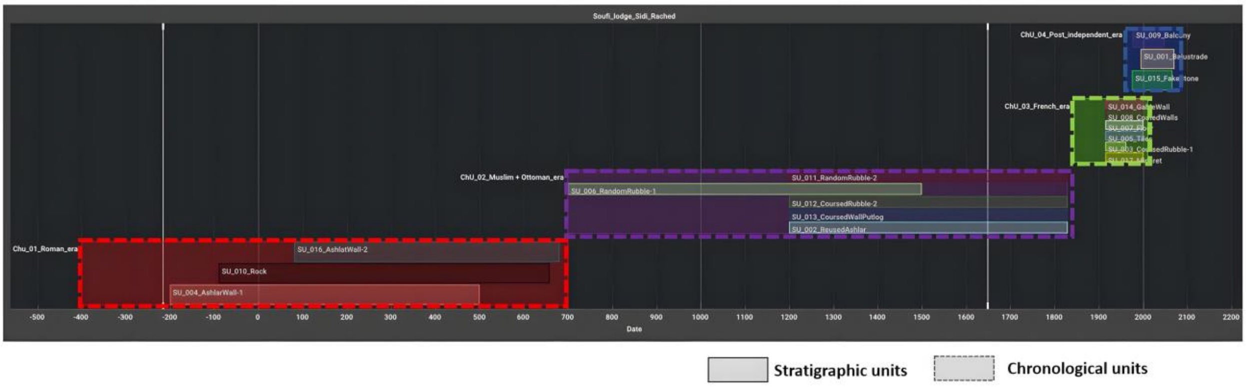

Fig. 6: The proposed chronological Graph for documenting stratigraphy

3.4. Data integration and multimodal visualization

To conduct a holistic study and gain a comprehensive understanding of stratification in its multidimensionality, the collected and structured data must be simultaneously visualizable and manipulable. While the annotation of temporal data around the 3D model enables to represent the chronological dimension of SBUs, it falls short in conveying sequences, durations and intervals. Conversely, the developed timelines represent effectively lifespans, antero-posteriority, and simultaneity relationships, yet they do not capture the spatio-morphological configuration or the topological correlations among temporal units.

A review of the literature underscores the convenience of multimodal representation tools, which facilitate an integrated approach and foster synergy between the diverse datasets and types of information generated (De Luca et al., 2011; Rodríguez-Gonzálvez et al., 2019; Stefani et al., 2011).

For this study, we used a stratigraphic viewer, developed for multidimensional visualization of heritage patterns developed by Haouacha et al. (2025). This software allows the display of 3D models enriched with integrated labels and temporal data linked to each SBU, presented within information fields. It also generates timelines that follow the same codification system as the SBUs in the point cloud. The tool serves two main purposes: first, it consolidates all collected spatio-temporal data and information within a single workspace; second, it links the different forms of representation—3D models, timelines, and attribute—into an interactive and coherent model. The population of attribute fields triggers real-time updates across the various graphical representations, while manipulating the timelines dynamically displays the corresponding parts of the building. Figure 7 depicts the GUI and the multimodal representation.

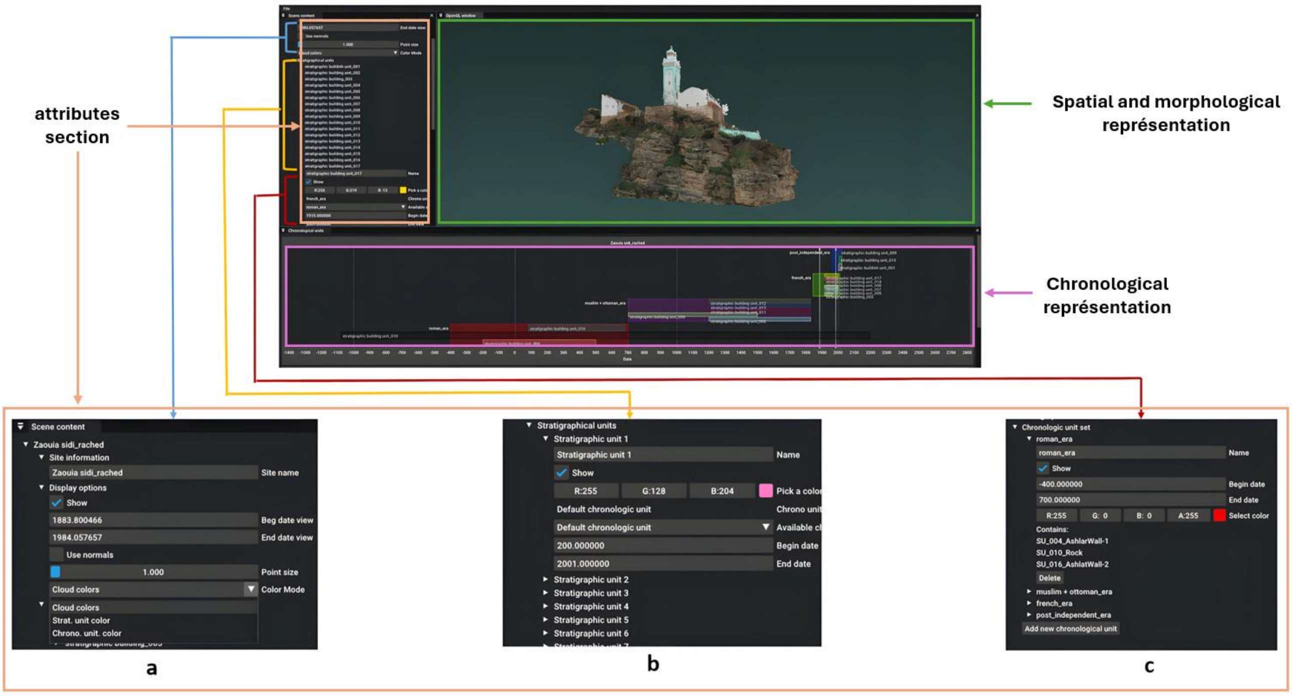

Fig. 7: The stratigraphic data viewer GUI

a : Site information, **b :** Stratigraphic building unit information, **c :** Chronological unit information

4. Results

4.1. Decoding the Spatial and morphological Layers of Stratigraphic Data

Using 3D reality-based models as supports for surveying and processing stratigraphic data enables highlighting the spatial organization of various types of information acquired during the study, thereby enhancing interpretive insight. The segmentation and filtering of the point cloud based on statistical and visual features allow for the clustering of different components into distinct layers, which in turn facilitates the visualization of the spatial distribution of each SBU within its local reference system. figure 8a shows the relative position of all coated walls corresponding to the structure built between 1915 and 1920, in relation to the earlier building. It is obvious that this intervention was carried out exclusively on the upper part of the older structure, as an extension or refurbishment of the former building. Similarly, the selective display of classified ashlar walls in Figure 8b enables a reading of the continuity between distinct parts belonging to the same construction element. The highlighted fragments —in blue—belongs to the same construction activity. They represent sections of the Roman defensive wall of the city; their respective locations help reconstruct the boundaries of this historical structure, which clearly extended beyond the current urban area. This is further supported by the discovery of similar fragments around the perimeter of the historic city, suggesting that part of the rampart was either partially demolished or collapsed.

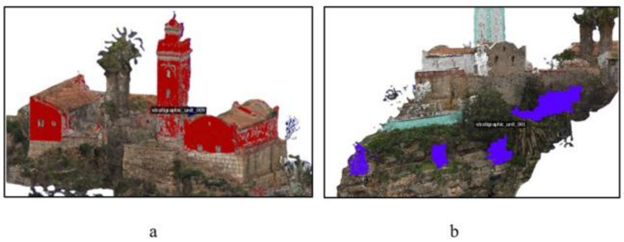

Fig. 8: Stratigraphic building units' visualization

a) Stratigraphic building unit built between 1915 and 1920 era, **b)** vestiges of the rampart of the antique Roman city

At a more-detailed scale, the supervised automatic segmentation revealed localised overlaps in labelling between different stratigraphic entities on the north-eastern façade —based on the manually annotated samples to train the classifier— as can be seen in Figure 9a. Close examination of both areas revealed that materials from the lower part of the wall were reused in the subsequent repair of the upper part. This later intervention integrated both recycled and new materials, employing a different construction technique compared to the older construction, mainly irregular joint thicknesses, and the use of bricks, rubble, and small stonework

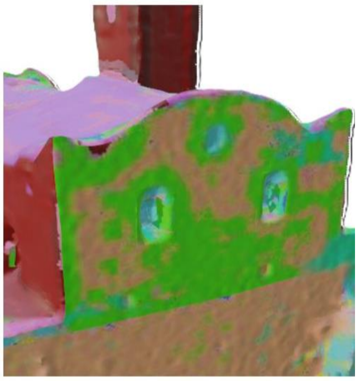

Fig. 9: ML supervised texture-based segmentation

The stone-by-stone segmentation performed on the upper part of the northeast façade, provides a clear representation of the diversity of masonry types (Figure 10a) and the irregularity of mortar joints used in the construction of the wall (Figure 10b). The area outlined in red indicates a material loss at this zone, which was subsequently repaired by filling the gaps with mortar and rubble.

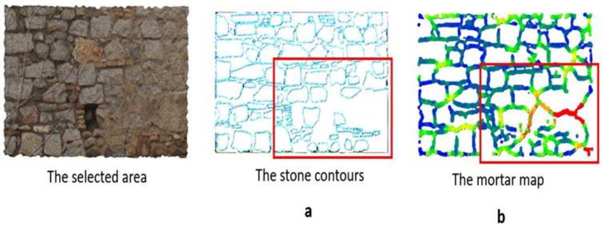

Fig. 10: individual masonry segmentation
a) Shapes of stones, **b)** mortar thickness and depth

With regard to the temporal dimension, the 3D digital model enables the isolation and visualization of distinct SBUs within their corresponding chronological phases. Figure 11 illustrates a chronological unit that spans from the Muslim era —after the Islamic Conquest in the 7th century— to the second half of the French colonial period —around 1910. As the analysis progresses, this unit can be further subdivided into several chronological subunits. The isolation of those phases reveals multiple extensions and/or merging interventions involving adjacent buildings. This three-dimensional approach has proven to be highly reliable for inferring past states and identifying successive stratigraphic cycles, particularly in densely built environments.

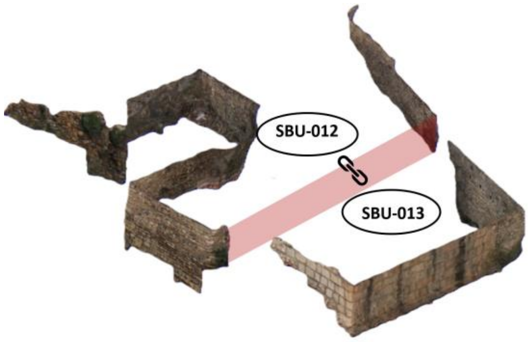

Fig. 11: Visualising of a chronological unit on the space.

4.2. Modelling a Quantified Chronology for buildings stratification

The proposed representation of the building's stratigraphic components through timelines facilitates a transition from basic relative relationships to a more in-depth, quantified chronology. Each SBU axis represented in the timeline is identified by a unique ID, colour coding, and defined start and end dates, enabling direct linkage to its corresponding part in the 3D model. This process anchors each abstract timeline to its physical location within the artefact through colour codification as can be seen in (Figure 12).

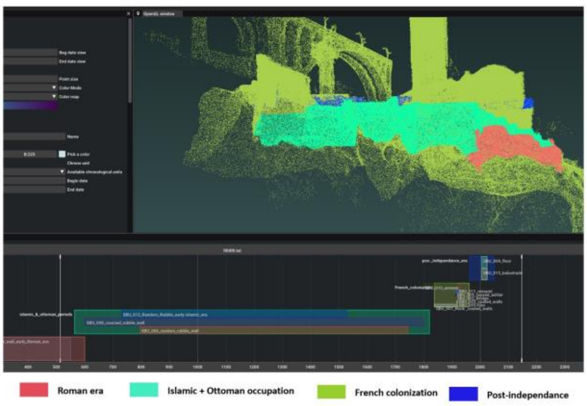

Fig. 12: Colour-coded thematic representation of chronological units

Furthermore, structuring SBUs along successive temporal axes, encapsulated within chronological fields, highlights their mutual temporal relationships—both between different SBUs and between SBUs and containing Chronological Unit. This structure also allows for identifying stratigraphic cycles, which define successive morphological states of the building throughout its genesis.

Moreover, the use of timelines to display chronologies makes it possible to visualise not only the order of occurrence of the different SBUs but also intervals of simultaneity between them. Given the modular nature of the proposed graph, users can isolate and examine specific, well-defined phases within the building's full lifespan for closer analysis and visualization. This proves especially useful in cases of long-term, densely stratified structures. In Figure 13, the displayed chronological unit aggregates multiple SBUs corresponding to relics from the stratigraphic cycle belonging to the period from the early Muslim conquest to the end of the Ottoman era. Those SBUs exhibit clear signs of succession –as illustrated in the timeline graphic- but lack precise documentation. However, as the timelines modelling is based on the introduction and population of data input, new chronological sub-units can be generated as more data are gathered over time. This method of data recording supports both the retrieval and ongoing updating of information as knowledge and discoveries evolve.

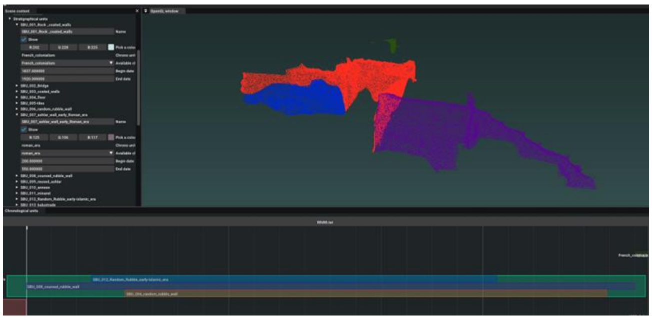

Fig. 13: Thematic map with colour-coded stratigraphic building units from a specific period

4.3. *Holistic and integrated visualization of architectural stratigraphy*

The integration of various graphic and non-graphic data within a unified workspace has enabled dynamic interaction among the different types of collected information, as well as the cross-referencing of data to support a more comprehensive understanding of the transformation process. The tool includes a temporal delimitation feature, accessible through scroll bars on the timeline as shown in Figure14, which allows users to isolate and display the building parts situated within a defined time-frame. This functionality enables the visualization of the building's omponents corresponding to a specific time T(x), marking the transformation spots. Such temporal filtering can help to identify and explain the causes and consequences of particular morphological configurations. Figure 14 illustrates the SBUs of the Sidi-Rached Sufi lodge which existed both before and after the construction of the bridge. This comparison enables us to speculate about the impact the bridge's construction had on the surrounding environment. Additional research supported this hypothesis. An article from a 1915 press release by Cuttoli (La Dépêche de Constantine, 1915), preserved in the archives, reports the significant deterioration of neighbouring buildings following the bridge's construction. It also highlights the urgent need to rehabilitate the Sufi lodge, formerly a mosque.

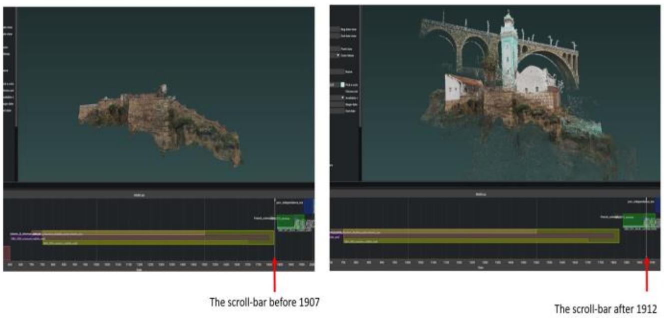

Fig. 14: Morphological evolution visualised through interactive timeline navigation
a) The parts built before 1907, **b)** the parts built after 1912

5. *Discussion*

The workflow presented in this paper highlights the contribution of reality capture techniques and information visualization (InfoVis) tools to stratigraphic reading, and proposes a methodological approach to support the understanding of diachronic buildings morphologies. By leveraging, the visual, geometric, and statistical metadata of reality-based 3D models this approach enables more accurate identification and classification of stratigraphic data. It represents a significant advancement, assisting professionals in the detection, interpretation, and organization of stratigraphic information, particularly in situations of data abundance or when operating in highly constrained sites—Such as sites that are difficult to access or present significant safety hazards like the presented case study. The various segmentation methods developed in the literature help overcome the inherent slowness and complexity of visual surface analysis and data extraction. They also assist in detecting subtle features that may elude even experienced professionals.

The proposed approach positions itself as a methodological and pragmatic alternative to the Harris method. It is specifically adapted to the architectural field and built heritage, where constructive, spatial, and material logics require a contextualised and multidimensional reading of stratigraphic phenomena.

The proposed workflow shifts the investigative phase, traditionally conducted in the field, to a more accessible and controllable digital environment. It also highlights the transition from a cumulative understanding of genetic logic to an integrated, interoperable and multidimensional reading of stratigraphic relationships. In addition, it moves from relative chronology to quantified and relative chronology, enabling a more precise interpretation of the sequential evolution of the built fabric.

Figure 15 illustrates and synthesises the main contributions and advances achieved in this research in the field of architectural stratigraphy.

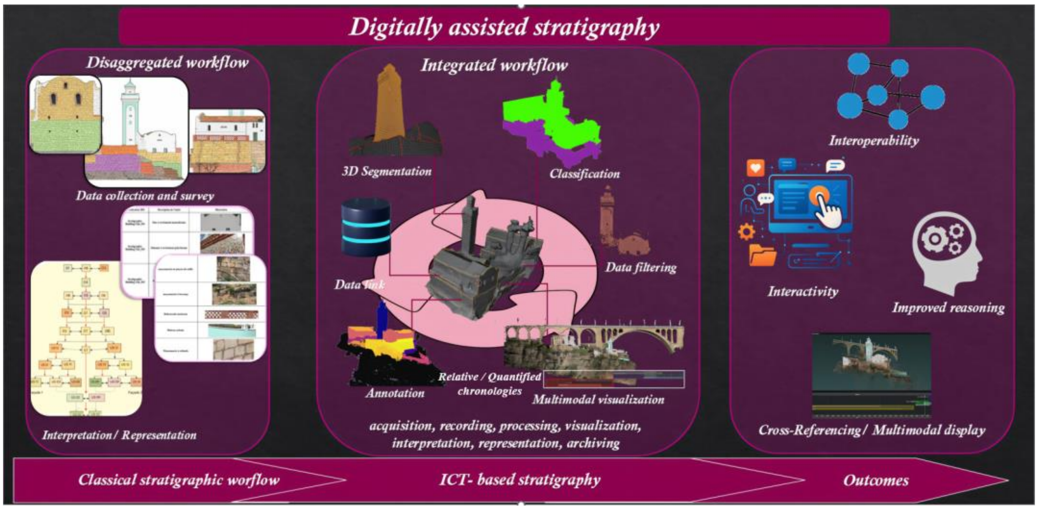

Fig. 15. Classical vs. ICT-based stratigraphic method: contributions of the ICT-based approach.

Despite substantial progress in 3D processing techniques, certain limitations remain. Ongoing research in 3D masonry segmentation is achieving notable results; however, challenges persist, especially in terms of material reusability, occlusion, material deterioration, irregular mortar joint thickness, and the variability in stone shapes, sizes, and colours. As a result, classification still demands human visual and manual assistance to ensure the reliable identification of stratigraphic components.

To address this, the integration of domain ontology for architectural stratification could offer a more precise description and definition of multilayered construction patterns. Such semantic enrichment of 3D models would enhance segmentation tasks by enabling filtering, advanced querying and data cross-referencing (Colucci et al., 2021; Messaoudi et al., 2019).

Furthermore, the integration of geometric and temporal data, along with the interlinking of various temporal datasets within a timeline, has enhanced analytical insight and improved interpretative accuracy. In addition, thematic mapping and data filtering techniques have proven effective in supporting and refining reconstruction hypotheses, while also playing a key role in assisting decision-making and planning of conservation works.

6 *Conclusion and future works*

This research discusses digitally assisted stratigraphy as a methodological framework for surveying and interpreting the morphogenesis of multi-layered built heritage. The study reviews advancements in reality capture technologies and information visualization tools (InfoVis), leveraging their capabilities to support both the analytical phases and the reasoning work.

In the proposed workflow, 3D models serve not merely as representational tools for mapping and visualising stratification, but also as active analytical supports. They enable the extraction, processing, and interpretation of stratigraphic data, thereby enhancing the understanding of built heritage and contributing to knowledge production. The automation of processing, based on intrinsic features of the generated 3D models helps moderating the traditional slowness and complexity of on-site stratigraphic surveys. This has led to new readings and interpretations previously undetectable, which are particularly valuable in large-scale and densely stratified contexts.

To address the chronological dimension of stratigraphy, the introduced timeline-based graphic proves highly effective for sequencing SBUs. This visual tool supports the identification of permanencies, coexistences, and lifespans, offering a clearer overall picture of the building's evolutionary process.

Furthermore, digital models foster interoperability, interactivity, and data connectivity across multiple platforms and tools. This facilitates enhanced collaboration and information exchange among heritage professionals, ultimately improving documentation of past-state and intervention decision-making. The approach also supports multi-scalar analysis, ranging from extensive heritage complexes down to stone-by-stone examination.

However, the reliability of digital data processing relies heavily on the quality of reality-based 3D models. Challenges such as occlusions, buried elements, and significantly degraded areas can limit the completeness and accuracy of the analysis.

The case study conducted on Sidi-Rached Sufi lodge demonstrated the effectiveness of the digitally assisted stratigraphy to address the multidimensionality of diachronic works of built heritage in a holistic and comprehensive manner. However, for further evaluation and validation of the proposed workflow, additional experimental studies should be conducted on a variety of building typologies and scales, including modern non-masonry heritage assets and urban ensembles. This will be essential to further assess and refine the proposed methods and tools, ensuring their adaptability and effectiveness across a broader spectrum of built heritage contexts.

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References

Abergel, V., Manuel, A., Pamart, A., Cao, I., & De Luca, L. (2023). Aïoli: A reality-based 3D annotation cloud platform for the collaborative documentation of cultural heritage artefacts. *Digital Applications in Archaeology and Cultural Heritage*, *30*, e00285. https://doi.org/10.1016/j.daach.2023.e00285

Aiello, C., Caruso, F., Cecalupo, C., & Kas Hanna, E. E. (2014). Photomodelling as an Instrument for Stratigraphic Analysis of Standing Buildings: The Baptistery of Albenga. *Rivista Di Archeologia Cristiana*, *90*, 259-293. https://www.academia.edu/14528427/

Al-Bakrī, Abū ʿUbayd ʿAbd Allāh. (1859). *Description de l'Afrique septentrionale* (W. MacGuckin de Slane, Trad.). Algeirs: Typographie Adolphe Jourdan. https://gallica.bnf.fr/ark:/12148/bpt6k56091900

Al-Idrīsī, M. (1250). *Nuzhat al-muštāq fī iḫtirāq al-āfāq (Tabula Rogeriana)*. Bibliothèque nationale de France. https://gallica.bnf.fr/ark:/12148/btv1b52000446t/f7.item

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*, *685*(10), Article 10. https://doi.org/10.3390/ijgi10100685

Blaise, J.-Y., & Dudek, I. (2008). Experimenting timelines for artefacts analysis: From time distribution to information visualisation. In *14th International Conference on Virtual Systems and Multimedia* (pp. 349–357). Budapest: ARCHAEOLINGUA. HAL SHS. https://hal.science/halshs-00357409

Brusaporci, S., Trizio, I., Ruggeri, G., Maiezza, P., Tata, A., & Giannangeli, A. (2018). AHBIM per l'analisi stratigrafica dell'architettura storica. *Restauro Archeologico*, *26*(1), 112-131. https://doi.org/10.13128/RA-23463

Busayarat, C., De Luca, L., Veron, P., & Florenzano, M. (2010). Semantic annotation of heritage building photos based on 3D spatial referencing. In *Proceedings of the 2010 Focus K3D Conference on Semantic 3D Media and Content* (pp. 1–5). France: CORE. https://core.ac.uk/outputs/43609850

Campisi, M. T., Giuliano, S., & Liuzzo, M. (2019). 3D integrated surveys and stratigraphic methods for a deeper understanding of historical buildings: A case-study of the Franciscan monastery and the Immacolata church in Troina, Sicily. *The ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W11*, 345-352. https://doi.org/10.5194/isprs-archives-XLII-2-W11-345-2019

Colucci, E., Xing, X., Kokla, M., Mostafavi, M. A., Noardo, F., & Spanò, A. (2021). Ontology-Based Semantic Conceptualisation of Historical Built Heritage to Generate Parametric Structured Models from Point Clouds. *Applied Sciences*, *11*(6), 2813. https://doi.org/10.3390/app11062813

Croce, V., Caroti, G., De Luca, L., Piemonte, A., & Véron, P. (2020). Semantic annotations on heritage models: 2D/3D approaches and future research challenges. *ISPRS - The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B2-2020*, 829-836. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-829-2020

Davies, M. (1987). The archaeology of standing structures. *Australian Journal of Historical Archaeology, 5*, 54-64.

De Luca, L., Busayarat, C., Stefani, C., Véron, P., & Florenzano, M. (2011). A semantic-based platform for the digital analysis of architectural heritage. *Computers & Graphics*, *35*(2), 227-241. https://doi.org/10.1016/j.cag.2010.11.009

Demetrescu, E. (2015). Archaeological stratigraphy as a formal language for virtual reconstruction. Theory and practice. *Journal of Archaeological Science*, *57*, 42-55. https://doi.org/10.1016/j.jas.2015.02.004

Demetrescu, E. (2018). Virtual Reconstruction as a Scientific Tool: The Extended Matrix and Source-Based Modelling Approach. In S. Münster, K. Friedrichs, F. Niebling, & A. Seidel-Grzesińska (Éds.), *Digital Research and Education in Architectural Heritage* (p. 102-116). Dresden, Germany: Springer, Cham. https://doi.org/10.1007/978-3-319-76992-9_7

Desachy, B. (2008a). *De la formalisation du traitement des données stratigraphiques en archéologie de terrain* [doctoral dissertation, Université Panthéon-Sorbonne - Paris I]. HAL. https://theses.hal.science/tel-00406241

Desachy, B. (2008b). Le Stratifiant, un outil de traitement des données stratigraphiques. *Archeologia e Calcolatori, XIX, 187-194*.

Diara, F., & Rinaudo, F. (2020). Building archaeology documentation and analysis through open source hbim solutions via nurbs modelling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B2-2020*, 1381-1388. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1381-2020

Discamps, E., Thomas, M., Dancette, C., Gravina, B., Plutniak, S., Royer, A., Angelin, A., Bachellerie, F., Beauval, C., Bordes, J.-G., Deschamps, M., Langlais, M., Laroulandie, V., Mallye, J.-B., Michel, A., Perrin, T., & Rendu, W. (2023). Breaking Free from Field Layers: The Interest of Post-excavation Stratigraphies (PES) for Producing Reliable Archaeological Interpretations and Increasing Chronological Resolution. *Journal of Paleolithic Archaeology*, *6*(1), Article 29. https://doi.org/10.1007/s41982-023-00155-x

Dudek, I., & Blaise, J.-Y. (2010). Understanding changes in heritage architecture: Can we provide tools & methods for visual reasoning ?. In *Proceedings IMAGAPP/IVAPP (pp. 91-100). Angers, France. HAL SHS. https://shs.hal.science/halshs-00564156v1*.

Féraud, L., (1868). Les anciens établissements religieux musulmans de Constantine. *Revue africaine, 12*(68), 121-133. https://gallica.bnf.fr/ark:/12148/bpt6k56979718/f1.item.r=salah

Forster, A., Valero, E., Bosché, F., Hyslop, E., & Wilson, L. (2023). Digital Toolkit to Assist the Interpretation of Traditional Masonry Construction. *International Journal of Architectural Heritage*, *18*(5), 725–739. https://doi.org/10.1080/15583058.2023.2182729.

Galera-Rodríguez, A., Angulo-Fornos, R., & Algarín-Comino, M. (2022). Survey and 3D modelling of underground heritage spaces with complex geometry: Surface optimisation for association with HBIM methodology. *SCIRES-IT - SCIentific RESearch and Information Technology*, *12*(1), 177-190. https://doi.org/10.2423/i22394303v12n1p177

Genovez, S. C. (2012). *Análise Estratigráfica : Uma Contribuição Ao Projeto De Restauro* [doctoral dissertation, University of São Paulo]. Biblioteca Digital de Teses. https://doi.org/10.11606/d.16.2012.tde-20062012-161333

Grilli, E., Dininno, D., Marsicano, L., Petrucci, G., & Remondino, F. (2018). Supervised segmentation of 3D cultural heritage. In Addison, A and Thwaites, H (eds.), *3rd Digital Heritage International Congress (DigitalHERITAGE) Held Jointly with (VSMM 2018)*, (pp. 1-8). San Francisco, CA, USA: IEEE.

Grilli, E., Dininno, D., Petrucci, G., & Remondino, F. (2018). From 2D to 3D supervised segmentation and classification for cultural heritage applications. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2*, 399-406. https://doi.org/10.5194/isprs-archives-XLII-2-399-2018

Haouacha, F. (2015). *L'etude de la stratification architecturale dans les monuments historiques pont el kantara de Constantine* [Magister thesis, BADJI MOKHTAR-ANNABA University]. https://biblio.univ-annaba.dz/wp-content/uploads/2019/02/These-Haouacha-Feriel.pdf

Haouacha, F., Ravaglia, J., & Boufenara, K. (2025). A Stratigraphic Information System for the Study of Architectural Heritage Assets' Morphogenesis. *International Journal of Architectural Heritage*, 19(12), 3261–3282. https://doi.org/10.1080/15583058.2025.2492239.

Harris, E. C. (1979). The Laws of Archaeological Stratigraphy. *World Archaeology*, *11*(1), 111-117.

Honoré, F. (1910). The two highest masonry bridges in the world. *Scientific American*, *103*(2), 25.

International Council on Monuments and Sites. (1964). *International charter for the conservation and restoration of monuments and sites* (Venice charter).

International Council on Monuments and Sites. (1994). *Nara document on Authenticity*.

International Council on Monuments and Sites. (2008). *ICOMOS-Ename Charter for the Interpretation and presentation of Cultural Heritage Sites.*

International Council on Monuments and Sites. (2011). *The Valletta Principles for the Safeguarding and Management of Historic Cities, Towns and Urban Areas*.

La Dépêche de Constantine. (1915, December 9).Gallica. https://gallica.bnf.fr/ark:/12148/bd6t51165905s

Manuel, A., De Luca, L., & Véron, P. (2014). A Hybrid Approach for the Semantic Annotation of Spatially Oriented Images. *International Journal of Heritage in the Digital Era*, *3(2)*, 305-320. https://doi.org/10.1260/2047-4970.3.2.305

May, K. (2020). The Matrix: Connecting Time and Space in Archaeological Stratigraphic Records and Archives. *Internet Archaeology*, 55. https://doi.org/10.11141/ia.55.8

May, K., Taylor, J. S., & Binding, C. (2023). Stratigraphic Analysis and The Matrix: Connecting and reusing digital records and archives of archaeological investigations. *Internet Archaeology*, 61. https://doi.org/10.11141/ia.61.2

Messaoudi, T., De Luca, L., Véron, P., & Halin, G. (2019). Vers une ontologie de domaine pour l'analyse de l'état de conservation du bâti patrimonial. *In Situ*, 39. https://doi.org/10.4000/insitu.22470

Murtiyoso, A., & Grussenmeyer, P. (2019). Automatic heritage building point cloud segmentation and classification using geometrical rules. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W15*, 821-827. https://doi.org/10.5194/isprs-archives-XLII-2-W15-821-2019

Neubauer, W., Traxler, Ch., Lenzhofer, A., & Kucera, M. (2018). Integrated Spatio-temporal Documentation and Analysis of Archaeological Stratifications Using the Harris Matrix. In: Fellner, Dieter W. (Ed.), *Proceedings of the 16th Eurographics Workshop on Graphics and Cultural Heritage* (pp. 235–239). Vienna, Austria: Eurographics Association.

Nguyen, A., & Le, B. (2013). 3D point cloud segmentation: A survey. In: *6th IEEE Conference on Robotics, Automation and Mechatronics (RAM 2013)* (pp. 225-230). Manila, Philippines: IEEE. https://doi.org/10.1109/RAM.2013.6758588

Pellis, E., Murtiyoso, A., Masiero, A., Tucci, G., Betti, M., & Grussenmeyer, P. (2022). An image-based deep learning workflow for 3D heritage point cloud semantic segmentation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVI-2/W1-2022*, 429-434. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-429-2022

Rodríguez-Gonzálvez, P., Campo, Á., Muñoz-Nieto, Á., Sánchez-Aparicio, L., & González-Aguilera, D. (2019). Diachronic Reconstruction and Visualization of Lost Cultural Heritage Sites. *ISPRS International Journal of Geo-Information*, *8(2)*, 61. https://doi.org/10.3390/ijgi8020061

Roskams, S. (2020). The Post-excavation Analysis and Archiving of Outputs from Complex, Multi-period Landscape Investigations: The example of Heslington East, York. *Internet Archaeology*, 55. https://doi.org/10.11141/ia.55.7

Santoni, A., Martín-Talaverano, R., Quattrini, R., & Murillo-Fragero, J. I. (2021). HBIM approach to implement the historical and constructive knowledge. The case of the Real Colegiata of San Isidoro (León, Spain). *Virtual Archaeology Review*, *12*(24), 49-65. https://doi.org/10.4995/var.2021.13661

Stathopoulou, E.-K., & Remondino, F. (2019). Semantic photogrammetry – boosting image-based 3D reconstruction with semantic labeling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W9*, 685-690. https://doi.org/10.5194/isprs-archives-XLII-2-W9-685-2019

Stefani, C. (2010). *Maquettes numeriques spatio-temporelles d'edifices patrimoniaux: une approche pour la modelisation de la dimension temporelle et multi-restitutions d'édifices* [Doctoral dissertation, l'École Nationale Supérieure d'Arts et Métiers - ParisTech]. Pastel.HAL.science. https://pastel.hal.science/pastel-00522122v1

Stefani, C., Brunetaud, X., Janvier-Badosa, S., Beck, K., De Luca, L., & Al-Mukhtar, M. (2012). 3D Information System for the Digital Documentation and the Monitoring of Stone Alteration. In M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino, & R. Caffo (Éds.), *Progress in Cultural Heritage Preservation Vol. 7616*, (pp. 330-339). Cyprus: Springer- Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-34234-9_33

Stefani, C., De Luca, L., Véron, P., & Florenzano, M. (2011). A Tool for the 3D Spatio-Temporal Structuring of Historic Building Reconstructions. In J. Al-qawasmi, Y. Alshawabkeh, F. Remondino (Eds.), *digital media and its applications in cultural heritage* (pp. 153–168). Amman, Jordan: CSAAR Press.

TALE: The Archaeology Lecture E-library. (2016, april 8). Layt. J (L-P Archaeology) *The Matrix Reloaded: Explorations in Directed Acyclic Graphs* [video]. https://www.youtube.com/watch?v=geLD7Fo6crU

Tirello, R., & Vilella, A. (2015). Archaeology of architecture: The evaluation of the Harris matrix to architectural stratifications. In B. Bowen, D. Friedman, T. Leslie, & J. Ochsendorf (Eds.), *Proceedings of the Fifth International Congress on Construction History* (pp. 455–462). Chicago, IL: Construction History Society of America.

Traxler, C., & Neubauer, W. (2009). *The Harris Matrix Composer*—A New Tool to Manage Archaeological Stratigraphy. In K. Fischer Ausserer (Ed.), *CHNT 13,– Proceedings of the 13th Workshop Archäologie und Computer*. Vienna, Austria: Museen der Stadt Wien – Stadtarchäologie.

Trizio, I., Marra, A., & Savini, F. (2022). Stratified traces on historic masonries. Interpretations and reconstructive hypotheses. *In C. Battini & E. Bistagnino (Eds.), Dialogues. Visions and visuality. Witnessing Communicating Experimenting. Proceedings of the 43rd International Conference of Representation Disciplines Teachers* (pp. 1127-1144.). Milano, Italy : FrancoAngeli.

Uk International Council on Monuments and Sites. (1990). *Guide to Recording Historic Buildings*.

Vandenabeele, L., Loverdos, D., Pfister, M., & Sarhosis, V. (2023). Deep Learning for the Segmentation of Large-Scale Surveys of Historic Masonry: A New Tool for Building Archaeology Applied at the Basilica of St Anthony in Padua. *International Journal of Architectural Heritage*, 18(11), 1749–1761. https://doi.org/10.1080/15583058.2023.2260771

Villalobos, R. (2024). A new proposal for the Architectural Stratigraphic Analysis and the resulting diagram. *Acta IMEKO*, 13(2), Article 2. https://doi.org/10.21014/actaimeko.v13i2.1729

Viollet-le-Duc, E. (1854). *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle*. Paris: Bance-Morel.