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Towards the definition of Transformation Stratigraphic Unit (TSU) as new section of the extended matrix methodology

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ABSTRACT
This study explores the interpretation of degradation and alteration phenomena as stratigraphic units, showing the preliminary results of ongoing research concerning new investigative methods and tools useful to formalize transformative processes on built heritage, in a chronological perspective. Merging conservation sciences with archaeology, the study introduces a new section of the Extended Matrix (EM) method: the Transformation Stratigraphic Unit (TSU). The aim of this work is to assess a new method for documenting and investigating cultural heritage, by generating scientifically reliable reconstructive hypotheses, and by analysing and comparing the mutual interaction of different degenerative phenomena and their relationship. The current workflow, still tentative, utilizes open-source tools and is designed to be replicable and it has been applied to the case study of the architectural complex of S. Pietro in Segni (RM).

Section: RESEARCH PAPER

Keywords: stratigraphy; extended matrix; transformation stratigraphic unit; virtual reconstruction; conservation; degradation phenomena; cultural heritage

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1. INTRODUCTION

The primary goal of this work is to demonstrate how degradation and alteration processes can be interpreted as stratigraphic phenomena, promoting an interdisciplinary approach that merges conservation sciences with stratigraphy-based disciplines such as archaeology. This perspective offers new ways of reading cultural heritage, emphasizing the importance of an integrated view that considers material accumulation and transformation over time as key elements for analysis and preservation.

The results achieved by applying this new section of the Extended Matrix (EM) are illustrated through the ongoing study of the architectural complex of S. Pietro in Segni (RM), which includes the analyses of both state of conservation and stratigraphy.

Alteration and degradation phenomena cause important changes in the general appearance of historical architectures and artefacts. The importance of protecting and studying the tangible evidence on historical surfaces has been a well-known issue and a subject of discussion during the last century and it is still relevant [1], [2], [3], [4]. To propose a solid scientific background to this approach, this paper presents an open and generalised formal tool, the Transformative Stratigraphic Unit (TSU), to trace the chronological sequence of degradation processes, providing a dynamic, time-encompassed view that traditional methods might overlook. This tool allows us to record and visualise not only the current state of preservation but also all the transformative processes of degradation and alteration associated with the life of a historic building. By mapping the chemical and physical changes that have occurred on specific surfaces, a detailed picture of additive, subtractive, or property change transformations concerning specific stratigraphic objects is provided.

Many studies have been conducted on the analysis and surface characterization of monuments and objects to extract and highlight relevant information about the state of conservation and degradation of surfaces [5] also using advanced 3D tools and methods to inspect the subsurface features [6]. However, these studies typically focus on the chronological horizon of the monument at the time of the mapping. Minor attention has been dedicated to the state of conservation and the alteration process. Only in a restricted number of cases, an attempt has been made to record, from a stratigraphic point of view, the historical moments in which processes of degradation were formed. In the field of archaeology, on the other hand, some macroscopic phenomena are already managed as negative stratigraphic units, meaning destructions or changes in the state of surfaces, but without providing a complete characterization of conservation or degradation study as in conservation science. This situation emphasizes the gap between the momentary focus of traditional conservation studies and the historical depth offered by archaeological methods, suggesting a need for an approach that combines these perspectives to achieve a more comprehensive understanding of degradation processes over time.

Recognizing all the modifications of surfaces is therefore essential not only to identify suitable restoration solutions but also to appropriately examine the objects of study, specially built heritage. Architectural finishes, for example, play a crucial role in studying ancient construction techniques and understanding possible different *facies* belonging to previous phases [7]. However, the analysis of architectural surfaces, especially the undecorated ones, often shows a lack of depth which leads, in most cases, to planning rough interventions, losing the authenticity of the artefacts and, eventually, creating a potential fabrication of history. As a result, the documentation process is fundamental for analysing and comparing the mutual interaction of different phenomena and their relationship with the context. Often, documentation methods change and update as technology evolves. In light of these considerations, developing and testing newer and more accurate archiving methods is important. The more accurate the recording of every information, the greater the chances of recognizing the possible modifications to study, conserve, and propose evidence-based reconstructive hypotheses (virtually and/or physically). Moreover, both the examination and the documentation of the state of conservation of artefacts in a diachronic way support the study of the virtual reconstruction of structures and objects in terms of colour, texture/consistency, and roughness.

One of the key benefits of linking the analysis of degradation processes to stratigraphy consists of operating with a suite of innovative tools developed by the Digital Heritage Innovation Lab (DHILab) of the Institute of Heritage Science (ISPC) of the National Research Council of Italy (CNR) of Rome and the Extended Matrix Community, to semantically manage this information within a 3D scenario. The Extended Matrix (EM) method -also developed by the DHILab- equipped with semantic annotation and information (with visual capabilities) based on stratigraphic granularity, serves as a binder for the representation of elements in their temporal depth, due to its features that allow annotation of both metadata and paradata related to reconstruction processes. This means not just pinpointing the era in which they were generated but, also, understanding how these phenomena occurred over a more extended period, rather than being confined to a single moment in time due to the use of traditional documentation methods. This approach makes it possible to illustrate the time span of every process by highlighting: the moments of beginning and end, the synchronicity of phenomena; the relationship between degradation and construction phase, etc. This study proposes a new section of the Extended Matrix method [8] to manage documentary accurately the temporal changes and physical transformations of stratigraphic objects over time in a single 3D environment.

Introducing the Transformative Stratigraphic Unit (TSU), this contribution represents one of the new branches that characterize a new stage on the development roadmap of the Extended Matrix method. Recently the EM method has related to HBIM [9] and GIS environments, such as QGis [10]; in the latter case using the plugin PyArchInit [11] as medium. In general, after almost 10 years, the method has been applied to document archaeological contexts, geophysics, and virtual reconstruction. By using TSU, the documentation phase will be enriched not only with more information but also with a clear three-dimensional layout. At this moment, can we compare EM with BIM? Yes, we can. EM does not represent a BIM example; Extended Matrix and BIM serve distinct yet complementary functions, both falling broadly within the realm of 3D Geographic Information Systems (GIS3D), which are computer systems that process spatial and geographic data connecting them with DBs. Despite this common ground, the two approaches diverge in their specialization areas: Extended Matrix focuses on stratigraphic and temporal aspects, analysing the historical evolution and layering of sites, whereas BIM is primarily aimed at simulation and management of buildings, covering both the preservation and the new interventions on historical structures. The collaboration between BIM and Extended Matrix is seen in treating Extended Matrix as an additional temporal dimension to BIM, thereby enhancing BIM's capability to manage and document architectural heritage. This synergy has led to the experimentation of interoperability scenarios, aimed at optimizing the management of historical-architectural information and planning for conservation interventions or new construction.

The following paragraphs treat the state of the art on the subject (2), the analysis of alteration and degradation processes as stratigraphic units (3), and its use in virtual restoration and reconstruction of lost construction phases (4). Subsequently, the methodology and tools that this research proposes (5) and the preliminary results obtained so far (6) are described. Finally, there is a section for discussion and conclusions (7), where opportunities and limitations of the work are analysed, also in comparison to other methods in use, and future perspectives (8) of the research are presented.

2. STATE OF THE ART

The Documentation related to the state of conservation of an artefact is the basis of every study on any type of cultural asset for conservation purposes. The degradation processes are investigated by all scientific disciplines to slow down or reset their course. The effects of the various degenerative pathologies are also studied to propose suitable restoration theories and methods, using materials and techniques compatible with the matter and what it represents [12], [13], [14]. However, surface mutations are also very significant for the study of different phases of cultural objects (e.g., construction, destruction, abandonment, etc.).

In Italy, the scientific debate on the exploration of a method to formalise the interpretative links between the fields of archaeology and architecture dates to the 1980s and 1990s when it was developed in the journals 'Archeologia Medievale' [15], [16] and 'Archeologia dell'Architettura' [17], [18]. These studies arose from the need to cross-reference different sources dialoguing with different disciplinary fields and continued to evolve to the present day with new research and the development of technology [19], [20].

The possibility of introducing transformation units into the stratigraphic matrix was proposed by Giovanni Leonardi and

Claudio Balista, who considered insufficient the normal data collection procedures in use by the ministry at the end of the last century [21]. According to them, the processes of accumulation (e.g., deposition) and subtraction (e.g., erosion) can be interpreted as a transformation phase, synchronous or post-depositional, equivalent to a non-static stratigraphic unit. Therefore, the Transformation Units, as theorized in the cited contribution, can document the alteration processes in a stratigraphic sequence. This approach allows new information aimed at evaluating, in a synchronic manner, the degradation, estimating the consequences of the state - inactive or persistent - and the historical 'position', as an effective tool for a systematic and codified control of the state of the art. Balista & Leonardi's theory was used also on architectural artefacts, as in the case proposed by Michele Asciutti on the SW tower of the Ss. Quattro Coronati Basilica in Rome. In that case, the shape of the moisture traces helped the interpretation of the lost construction phases. The chemical analysis results on different patinas allowed the reconstruction of the transformations that occurred in the use of the different rooms [22]. In the field of architectural restoration, Francesco Doglioni [23], [24] created a new graphic symbolism for recording traces observed on building surfaces. The method is based on archaeological stratigraphy, and it is focused on improving the interpretation of the "surface stratigraphy" [25].

Based on the stratigraphic principles, in 2015 a new approach, the Extended Matrix (EM), has been formalized to document, map and visualize the reconstructive process behind a virtual reconstruction of an archaeological context or an artefact [26]. Today, with this contribution, this new approach (the EM) has been used to establish, visualize and explore in 3D a connection between archaeological data and data related to both the state of conservation and the types of degradation that influenced the "life cycle" of an archaeological structure or an artefact.

3. THE ANALYSIS OF ALTERATION AND DEGRADATION PROCESSES AS TRANSFORMATION STRATIGRAPHIC UNITS (TSU)

Historical contexts and buildings are complex systems, which we investigate in a moment of their life path, in a temporary situation, during a period of continuous transformation. For example, architectural artefacts are usually formed by additions and subtractions, which took place at different times for different purposes, and by modifications due to the degeneration of matter. Archaeological investigations and state of conservation analyses are both fundamental and necessary to read the sequence of historical events on architectural surfaces, identifying the dynamics of the material transformations. The concept of degradation goes far beyond the natural decay of matter, since often its concrete manifestation is the evidence of a specific transformative dynamic of the object [21].

The theoretical core of the article is dedicated to the analysis of alteration and degradation processes, considered as Transformative Stratigraphic Units (TSUs). The investigation's importance lies in both the archaeological inquiry and the conservation state for interpreting stratigraphic sequences, highlighting how material alterations, and degradation phenomena change the external appearance of built heritage. Throughout the text specific examples, including cases of chromatic alteration, will be presented to illustrate the applicability of the methods.

Deterioration of a building and its transformation are inevitably intertwined with the history and evolution of the building itself, with its use and with its changes. Indeed, degradation phenomena are associated with the natural passage of time, they are connected to the physical history of the structure, the natural history of the materials that make it up, the atmospheric agents of degradation, the cultural history of its builders, and the direct interaction that human being have with structures or artifact [27]. Material alterations and degradations of the surfaces change the external appearance of the built heritage. Even in cases where the structure is still clearly recognizable, it is possible to identify degradation phenomena of the construction materials that can cause important changes in the general appearance of architectures and artifact. Therefore, coding degradation phenomena through stratigraphy could facilitate their recording as a "source" and their placement in a complete and more complex chronological framework in which each evidence is part of a larger historical moment.

Occasionally, the information on the conservation and degradation of surfaces aids in better interpreting the historical phenomenon, such as the case study of the church of San Pietro in Segni, which stands on the ancient acropolis of the city. This church was constructed over the remains of the Temple of Giunone Moneta, with the church adapting the central cell of the originally tripartite temple. When the original roof of the temple collapsed, the outer walls of the cell, which are now the exterior walls of the church, began to degrade. This is why the surface of the tuff blocks, cut in a squared manner within the church, are perfectly preserved, whereas the exterior facade has been significantly deteriorated by weathering. To virtually reconstruct how the outer wall of the cell appeared in Roman times, when it was covered by the roof that extended over the temple's lateral cell, it is possible to identify the stratigraphic transformative unit of the wall surface and map how it would have appeared in Roman times, using the internal wall as a comparison. Understanding the stratigraphic dynamic, namely the removal of the roof that protected the surface, allows for the dating and correct placement within the stratigraphic diagram of the transformative stratigraphic unit, that is, the transformation from a facade of perfectly preserved tuff blocks to a facade heavily eroded by the elements.

This example testifies that the archaeological information helps to understand how the degradation process was triggered, providing more input for restoration procedures. In other words, these two integrated approaches enrich the understanding of heritage conservation. The challenge lies in integrating them within the same workspace so that the data are coherent, accessible, and interoperable by those who need this information from different perspectives. This is why we introduce the concept of the Transformative Stratigraphic Unit (TSU), which allows expressing the idea of an element that transforms over time, interacting with its surrounding physical and environmental context. This integration emphasizes the symbiotic relationship between conservation science and archaeology, suggesting that a comprehensive understanding of heritage degradation requires combining these disciplines. The introduction of TSUs as a conceptual framework enables a nuanced interpretation of change over time, bridging the gap between static conservation data and dynamic archaeological records.

The tentative workflow proposed in this research divides the analysis phase into three moments. The first two deal with data collection and analysis. The first deals with the collections of all the useful sources connected to the case study. The second refers to the specific analysis of all the real tangible evidence (regarding stratigraphy and degenerative phenomena), useful to document construction phases and degenerative phenomena, with analysis of the pathologies concerning the different materials and stratigraphic units to which they belong. A final step of the research consists of a critical synthesis of the results derived from the comparison between the results of the analysis. This phase permits to both drawing conclusions for a potential virtual reconstruction of the historical phases of the building and using reconstructive data as a basis for any conservation, restoration, and enhancement interventions. It is noteworthy that the results of the first two steps represent a coherent output related to the documentation of the state of conservation of the monument. Eventually, the third step is about the possibility of using this within a reconstructive project.

The first general analysis of the different pathologies is mainly carried out through three types of sensorial interactions (sight, touch, and hearing). The documentation is carried out with the compilation of datasheets (one for each pathology) according to methods already in use [28] and with the Italian and international standards [29], [30]. Pathologies are identified with a code and are divided by type and category with progressive numbering. The documentation includes a general description of the pathology with the identification of any indirect signs, the recognition of other coexisting degenerative phenomena and a close-range description divided according to sensory perception. Finally, any in-depth diagnostic analyses recommended are listed and the possible causes are described. The filling activity is normally divided into four steps: 1) recognition of the various phenomena in progress; 2) autopsy analysis; 3) photographic documentation; 4) compilation of the data sheets and subsequently - where necessary - new in-depth investigations.

Considering all forms of degradation as stratigraphic units enables us to use the formalisms of the EM, that based its theoretical concepts on stratigraphy. The EM methodology consents to keep together both the documentation of the visible traces and the reconstructed parts, guaranteeing scientific reliability and replicability of the process in any archaeological and architectural context.

4. THE ANALYSIS OF DETERIORATION, PROCESSES FOR VIRTUAL RESTORATION AND RECONSTRUCTION

The analysis of deterioration processes and their integration with stratigraphy through the Transformative Stratigraphic Unit (TSU) is critically important for virtual reconstruction. The differentiation between well-preserved sections and degraded portions of objects is a critical aspect of virtual restoration, highlighting the importance of distinguishing those areas that have retained their chromatic quality and surface texture from those that have not. This principle also applies to paintings, where distinguishing between fragmented elements and those better preserved is essential for understanding how to reconstruct the fragmented or degraded parts based on the better-preserved elements. The analysis of degradation and conservation is fundamental to ascertain if these elements, which visually appear the best, are truly representative of what the entire artefact was in antiquity. Therefore, before undertaking a virtual restoration, it is paramount to understand the level of degradation of the elements and to correlate them with stratigraphy. This is particularly relevant when using a formalized approach for virtual reconstructions such as the Extended Matrix. By doing so, we can ensure that the virtual restoration or reconstruction not only visually approximates the original state but also adheres to the historical and material truths revealed through attentive stratigraphic analysis.

Virtual restoration and reconstruction activities do not consider the assumptions of durability, reversibility, sustainability, and compatibility of the materials and can be a valid investigation tool for the study of artefacts, for the verification of the reconstructive hypotheses and support for the design of possible real restoration interventions. However, any form of restoration must guarantee scientifically based reconstructive choices and coherence between the current state of the materials and their eventual return to pristine condition, whether material or virtual. In all cases, therefore, the first step, after the survey and the analysis of indirect sources, is the direct study of the material of the remaining structures with possible in-depth investigations, where it may be necessary. Carrying out accurate diagnostic campaigns is, in fact, a fundamental process of the intervention, as recognized by the 1972 Italian Restoration Chart [31].

The introduction of photogrammetry, with the consequent availability of increasingly accurate colour information and the ability to characterize the surfaces as they appear at the time of the survey, has led over the years to employ derived information as a starting point for the reconstruction of their original appearance. The risks of this method are self-evident. The possibility of not dealing with the material, the virtuality itself of the intervention, and the ease of quickly obtaining graphically captivating results have led to the proliferation of reconstructive models in which restoration and recovery practises merge in a perfectly mimetic way, making it impossible to distinguish the original portions from the reconstructed ones. The problem in these cases does not concern only the result, but the whole process underlying the obtaining of the final data.

This research proposes an operational method to avoid these problems and document the reconstruction and restoration choices as transparently as possible by dividing the information into two interoperable macro-systems: 1) the construction phases (and various modifications), which are a series of actions of a technical nature referring to a precise historical-cultural context, and 2) the alteration and degradation phenomena (structural or superficial) which are, instead, a series of actions originating in different fields and do not refer to conscious interventions [9], [10]. Therefore, the workflow divides the analysis phase into two parallel moments: the analysis of sources and the study of stratigraphy (when visible), useful to document the construction phases, and the documentation of degenerative phenomena with analysis of the pathologies of the different materials and stratigraphic units to which they belong. Subsequently, a critical synthesis is made of the considerations that emerged from the comparison between the two different surveys, to conclude the virtual reconstruction of the historical phases of the building to be finally used as a basis for any conservation, restoration and enhancement interventions.

5. METHODS AND TOOLS

The proposed approach is based on the implementation of the Extended Matrix method, adding the analysis of surfaces conservation as a valuable contribution to virtual reconstruction. To make it operational, this approach has been implemented within the EM as a new section of the method with a dedicated node (the TSU node) and features.

5.1. The new section of the Extended Matrix method

The Extended Matrix (EM) [14] consists of an Open Science Framework, the so-called Extended Matrix Framework (EMF), developed by the DHILab of the CNR-ISPC of Rome and the EM Community. The method has been designed to: create a comprehensive documentation of Heritage objects, with a strong focus on metadata and paradata provenance (which source documents, 3D surveys, etc. are included in the documentation), and implement a reconstruction pipeline digital, transparent, easy to understand, and repeatable.

EM refers to solid formal and theoretical bases such as the Harris Matrix and Stratigraphy, to manage the chronological sequence of events; CIDOC-CRM standards, to control data storage and data management; and Computer Graphic, to represent data within a 3D environment. The Extended Matrix method extends the Harris Matrix to document and map the reconstruction of an archaeological context. The so-called "extension" has been controlled with a formal language, which is composed of a proper node-based grammar, and some open-source software solutions. The latter are tools useful to manage reconstructive data and paradata within Blender (EMtools) [32], edit 3D geometries in the same 3D environment (3DSC) [33], and share online both 3D models and reconstructive information (EMviq) [34].

On this occasion, a novel section of the Extended Matrix method (the palette including the TSU is available online on the official repository) [35] has been used to digitally map, manage, and virtually visualize alterations and degradation phenomena of the monument. This new development of the method allows to register, within the EM graph, both information and geometrical annotations, concerning the state of conservation of the ancient monument, useful for reconstructive purposes.

As already mentioned, from an Extended Matrix point of view, to implement this new section of the method, it has been necessary to create a new part of the formal language, linked to the research field of conservation science. In this case, both a new node, the Transformation Stratigraphic Unit node (TSU node), and a new theoretical definition of the node itself have been formalized within the EM method.

Table 1. TSU Properties.

TSU properties	Notes
ID	id number
TSU	Transformation Stratigraphic Unit
ATP	Abbreviation Type Phenomenon
Typology	type of modification (a, b, c, d)
Phenomenon	Phenomenon codification
Localisation	Geographical location of the object of analysis
Date of survey	The moment when data has been registered
Element	Architectural/decorative element
Material	Type recognition of the altered/degraded material
Exposure	Orientation of the phenomenon based on cardinal points
Description	"5 meters from the altered area"
Close range description	Visual assessment
Close range description	Tactile assessment
Close range description	Hearing assessment
Indirect signs	Indirect sign of phenomena
Coexistent phaenomena of alteration/degradation	List of other coexistent degenerative phenomena
Analyses	Carried out and/or recommended in-depth analyses
Diagnostic conclusions/causes	Results of the analysis
Anteriority	*ante quem* relation
Posteriority	*post quem* relation
Contemporaneity	contemporary stratigraphy units

5.2. The TSU node

The TSU node stores in the EM graph all the information, the so-called "Properties" (Phenomenon, Localisation, Date of survey, Element, etc..; see Table 1), concerning the conservation status of the subject of a research/analysis and their chronological order of appearance. In the case of a reconstructive process, this information can be used as a new informative layer to improve the reliability of the reconstructive proposal. Therefore, within the method, the TSU node has been conceived as a real and tangible Stratigraphic Unit with a double scope. The TSU is both the witness of a transformation, an event that has changed the original aspect of a structure or an artefact (for instance: "erosion" can modify the external aspect; "chromatic alteration" can drastically change the original colour of finishes; "biological colonization" can mask the original layer of the surface; etc..), and a suitable source of information to support the reconstructive process (for instance: in the aforementioned case study of Ss. Quattro Coronati, the traditional TSU mapping allowed the identification of unknown previous construction phase of the structure [22]).

5.3. The Graphical conventions to represent TSUs, a work in progress

In our ongoing work on the graphical conventions for representing the Transformative Stratigraphic Unit (TSU), it is crucial to acknowledge that, as all stratigraphic units, the TSU requires a three-dimensional representation within the spatial domain. Typically, within the language of the Extended Matrix, a stratigraphic unit is depicted as a spatialized volume that encompasses the specific section of the wall structure it refers to, such as highlighting and enclosing a wall structure of the perimetral wall of the Temple of Giunone Moneta. When addressing the TSU, we encounter transformative units that may be very thin and extensive, spreading across the external surface of a wall structure or the exterior of an object. To geometrically describe such situations, it is necessary to represent the TSU as surfaces resting against other surfaces. Achieving this, while maintaining coherence and precision regarding thickness, required an immediate search for a technical, implementable, sustainable solution that could be visualized with the tools of computer graphics, namely polygonal meshes with a null thickness or equivalent to the thickness of the element being described, for example, the formation of a calcareous concretion with a thickness of 5-7 mm on the wall surface.

Currently, there are a few ways to create annotations in Blender: (i) extruding single points towards a direction; (ii) using the Grease Pencil command; (iii) using the Annotation command, and (iv) using the built-in knife tool of Blender. All these options allow the creation of meshes that can be employed as Proxy models (i.e., the three-dimensional representation of a node of the EM) within the 3D environment of Blender [19]. On the other hand, the theoretical improvement of the method, useful to map and manage the state of conservation data, has proceeded simultaneously with the development of the add-on employed to manage, and visualize in Blender EM nodes, paradata, and, if necessary, connected databases [19]. In the latter case, two principal actions have been carried out: 1) the add-on

EM tools have been taught to recognize and visualize the TSU node and its related data; 2) a set of new Blender materials have been realized starting from an already existing list of symbols designed by the CNR and the Istituto Centrale per il Restauro (ICR) guidelines [20]. Therefore, these materials have been included within an EMtools' material library to be applied automatically when a specific type of TSU is indicated in the EM graph. This step of the implementation requires the necessity, from the user perspective, to create a specific material for these TSU-Proxies. These materials allow us to easily represent each type of degradation (in this case, for every type of degradation a corresponding set of material has been created) and distinguish when multiple TSU-Proxies, referred to different types of TSUs, are overlapped (in this case, a material with an alpha channel for the background has been employed).

6. RESULTS

The experimentation was carried out on the church of S. Pietro in Segni during the project #SegniArcheologia [36], [37], [38] (Figure 1).

The structure, located in the ancient Acropolis of the city, was built on the remains of a Roman Republican temple consecrated to Giunone Moneta, and preserves the overlapping of multiple construction, abandonment, and restoration phases [39] (Figure 2). Today, the wall faces of the structure appear as an articulated palimpsest in which the identification of at least five different construction macro-phases is still possible. The first seems to coincide with the construction of a large podium in opus siliceum dating back to the Archaic age, on which stand the remains of the Roman temple built in opus quadratum. In late antiquity, the site seems to have undergone a period of neglect with the partial demolition of the architecture and the subsequent reuse of the structures for the installation of the medieval church, which also shows multiple constructive moments. The church consists of a single nave built in the main cell of the former temple. The medieval church may have had another small nave in the right wall where three large arches are still visible. Inside these arches, some frescoes dating back to the 13th and 15th centuries were discovered. From the comparison between the iconographic documentation and the direct study of the current conformation of the monument, it was finally possible to identify two further phases in the 19th and 20th centuries (Figure 3, Figure 4 and Figure 5).

Figure 1. Satellite image of Segni (RM, Italy). Within the red rectangle a focus on the location of the church of S. Pietro (http://www.bing.com/maps - © Vexcel Imaging - 2024 Microsoft)

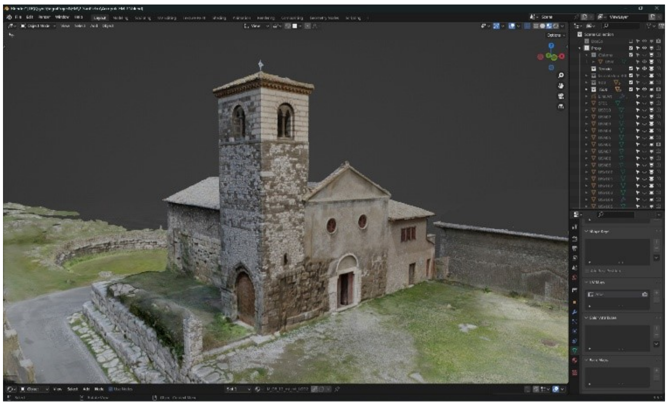

Figure 2. View of the photogrammetric model of the church of S. Pietro in Segni in Blender.

The state of conservation of the church of S. Pietro in Segni is fairly good. No portions of the optimal preserved wall facing, useful for a possible sampling of the texture, were found; however, some walls were built with well-known construction techniques that can be reconstructed by analogy based on already studied/published examples. The tuff employed in the opus

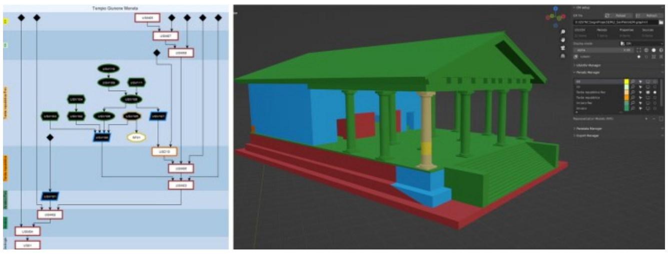

Figure 3. EM graph of the temple (left). Representation of the proxy models of the temple within Blender using the add-on EM tools (right). By following the structure of the graph, the add-on automatically applies the correct colour scale to the geometries. In red are SUs, existing *in situ* elements; in blue are Structural Virtual Sus (USV/s), restoration of an existing *in situ* element; in green are Non-Structural Virtual Sus (USV/n), a reconstruction which is not based on *in situ* elements; and in yellow are Special Finds, anastylosis of fragments.

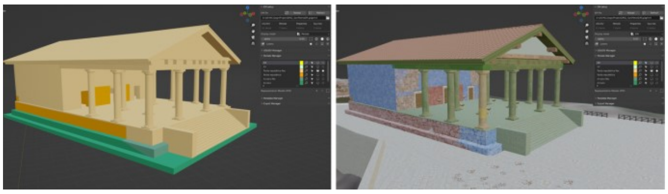

Figure 4. Proxy representation with colour scale relative to chronological scan (left) and proxy overlay on Representation Model (right).

Figure 5. Representation model of the Roman temple.

a.

b.

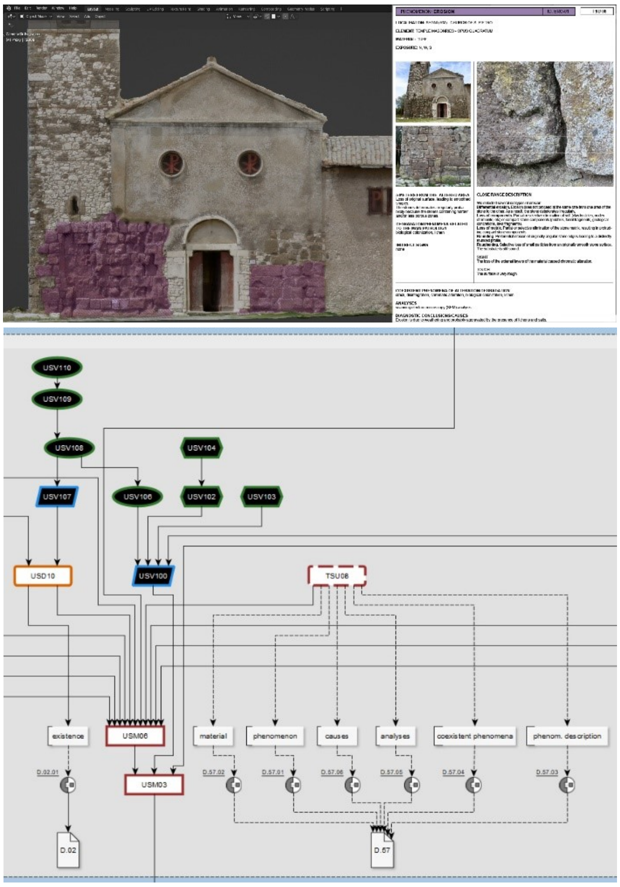

Figure 6. a) Proxy model of TSU08 [degradation pathology: erosion of tuff masonry] applied on the reality-based model in Blender (left). Preview of the corresponding data sheet - ID ERO01, document no.57 [D.57] (right). b) Detail of the EMGraph with TSU08 [erosion] related to USM06 [tuff block masonry].

quadratum walls of the temple is particularly subject to erosion and this has led to the loss of the entire outermost layer of the blocks and therefore of their surface processing. The elements today appear rounded and very porous, but it is possible to hypothesize that they must have been finely worked and smoothed and may also have had an additional finish for protective or decorative purposes.

Several degradation pathologies were found. The most representative ones were annotated on the 3D model and related to other SU on the EM graph. The SU were recognized in the field and filed. Subsequently, the various pathologies of degradation were analysed and mapped, dividing them according to type, material, and SU to which they were related. On the main façade of the church (south-facing), 1 alteration and 11 different degradation pathologies were detected. These pathologies were organized into 23 TSUs and related to 4 USM (Stratigraphic Unit of Masonry): TSU1-7 to USM06; TSU8-12 to USM07; TSU13-19 to USM08; TSU 24 to USM09 (Figure 6 and Figure 7).
In general, the add-on EMtools consents to represent, interact, highlight and edit in Blender any types of information that have been mapped in the Extended Matrix.

In the case study illustrated within this contribution, the add-on allows users to establish a link between the conservation data, stored for each TSU inside the EM graph, and the related geometries created in Blender [40]. In general, for each annotation on top of the digital replica of the church, the TSU-Proxies represent both a spatial location and an informative layer. With EM tools, users can: geometrically annotate both

a.

b.

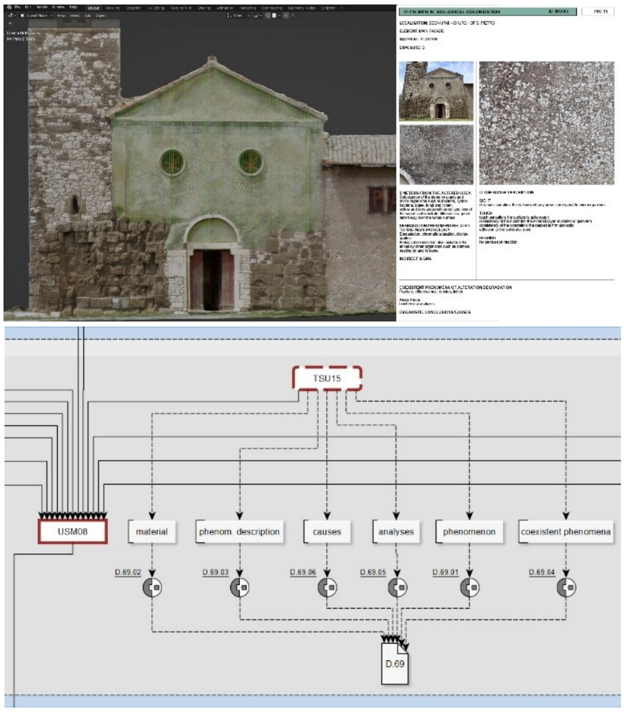

Figure 7. a) Proxy model of TSU15 [degradation pathology: biological colonisation] applied on the reality-based model in Blender (left). Preview of the corresponding data sheet – ID BIO03, document no. 69 [D.69] (right). b) Detail of EMgraph with TSU15 [bio colonization] related to USM08 [plaster finish].

alterations and degradation phenomena within a 3D space; visualize annotations within a 3D environment; consult within the 3D software all the information stored in the EM graph; and export data in csv\xlsx format.

At the moment, 24 types of alteration and degradation have been identified. To both distinguish all these typologies and automatically attribute them to the related geometries, through EMtools, as already mentioned, a new representation pattern is going to be implemented within the list of materials already embedded in the same add-on.

7. DISCUSSION AND CONCLUSIONS

In the past years, great progress has been made thanks to the standardization of different types of alteration and degradation pathologies.

This study wants to take the methodology to a new level with the use of innovative data acquisition and management tools. By following this tentative workflow, scientifically valid results can be obtained. All surfaces are examined with the same level of detail without distinction between decorated and undecorated parts.

The results described in this paper have outlined a promising perspective regarding the connection between the archaeology of architecture, strictly connected to chronology, and the conservation science field of research, based on surface analysis. With the mapping of pathologies and degradation accurately spatialized on the three-dimensional model through the Extended Matrix (EM) approach, we can broaden the use of this data for conservation and enhancement purposes. This is because the information will be preserved and structured within a graph database, where the Extended Matrix serves as a layout or synopsis, making the data accessible and reusable. It facilitates research within the graph database, particularly by employing future tools such as the CNR-ISPC Dataspace (dataspace.ispc.cnr.it), where data from various approaches and investigations converge within the same knowledge graph. This section of the Extended Matrix aims to act as a proposition for expanding international standards and extending them into three-dimensional representations.

The case study presented in this paper aims to affirm that integration with the Extended Matrix methodology enables the incorporation of degradation and conservation studies into a multidisciplinary domain. Within the Extended Matrix, it is possible to observe both the stratigraphy on the surveys and map the archaeological evidence, the features arising from the remote sensing and geophysics methods. Incorporating aspects related to conservation and restoration is crucial for fostering a dialogue on the same methodological table among different disciplines.

Limitations of this new investigation and documentation methodology are mainly related to the novelty of the instrument. The major issues concern the need to complete the formal definition of the tools and their usability. In addition, it will be necessary to test the new approach on more case studies.

8. FUTURE WORKS

The ongoing research has underscored the significance of integrating Transformative Stratigraphic Units (TSUs) within the Extended Matrix (EM) framework. This integration provides an immediate conceptual and ontological framework for the stratigraphic reading, interpretation, and sharing of data related to the conservation and degradation of surfaces and facilitates access to a multidisciplinary workspace. Within this space, the scientific community is already developing projects from various perspectives, ranging from stratigraphic readings in Building Archaeology, geophysics [40], and reconstructive hypotheses, to landscape rendering and integration with the Heritage Building Information Model (HBIM [9], [10]). Specifically, a version of TSU compatible with landscape degradation readings is slated for future development.

A key future objective is to shift the workflow as much as possible to the field, thereby collecting TSUs directly on-site with tools that enable semantic annotation of degradation surfaces. Another aspect involves sharing three-dimensional scenes through an adaptation of the existing concept, EMviq, to facilitate the online sharing of TSU data with other researchers for collaborative review and revision.

The most critical point of our current efforts is the development of a definitive version of EMTools capable of semantically annotating TSUs. This follows the creation of new algorithms that allow for the drawing of surfaces on geometries obtained from surveying techniques, such as photogrammetry or laser scanning.

This approach not only advances the methodology for documenting and analysing architectural and archaeological heritage but also enhances the collaborative and interdisciplinary nature of Heritage Science. By enabling semantic annotations and facilitating data sharing, we are paving the way for more integrated and comprehensive studies that can contribute significantly to the conservation, understanding, and appreciation of heritage sites on a global scale.

AUTHORS' CONTRIBUTIONS

Conceptualization, E.D and E.S.; methodology, E.D., E.S.; software, E.D.; validation, E.S., S.B.; formal analysis, E.S.; investigation, E.S., S.B. and E.D.; resources, E.D and E.S.; data curation, E.D., E.S: and S.B.; writing---original draft preparation, E.S., S.B and E.D.; writing---review and editing, E.S., S.B and E.D.; visualization, E.S. and S.B.; supervision, E.D.; project administration, E.D.; funding acquisition, E.D. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

[1] Superfici dell'architettura. Le finiture. G. Biscontin, S. Volpin (editors). Proc. of the 6th Convegno SBC, Padova, Italy, 26-29 June 1990, Libreria Progetto, Padova, 1990. [In Italian]

[2] GraDoc: Graphic Documentation Systems in mural painting conservation, W. Schmid (editor), Research seminar, Rome 16 - 20 November 1999, ICCROM: Rome, 2000

[3] F. Doglioni, Ruolo e salvaguardia delle evidenze stratigrafiche nel progetto e nel cantiere di restauro, Arquelogìa de la Arquitectura (2002) 1, pp. 113–130. [In Italian]

[4] Intervenire sulle superfici dell'architettura tra bilanci e prospettive. G. Biscontin, G. Driussi (editors), Proc of the 34th Convegno SBC, Bressanone, Italy, 3-6 July 2018, Edizione Arcadia ricerche, Marghera Venezia, 2018. [In Italian]

[5] D. Mendoza, M. Antonia, E. De-La-Hoz-Franco, J. Gomez, Technologies for the preservation of cultural heritage - a systematic review of the literature, Sustainability 15 (2023), 2, 1059. DOI: 10.3390/su15021059

[6] M. Cozzolino, A. De Simone, V. Gentile, P. Mauriello, A. Piezzo, GPR and Digital Survey for the Diagnosis and the 3D Representation of the Battle of Issus Mosaic from the House of the Faun, Pompeii (Naples, Italy), Applied Sciences 12 (2022), 6965.
DOI: 10.3390/app12146965

[7] G. Carbonara, L. Barelli, Il valore documentale delle finiture e l'importanza della loro conservazione: l'imitazione del passato nella falsa cortina laterizia dipinta a Roma nel Medioevo, in: Il potere dell'arte nel Medioevo. Studi in onore di Mario D'Onofrio. M. Gianandrea, F. Cangemi, C. Costantini (editors). Campisano Editore, Roma, 2014, ISBN 978-88-98229-30-7, pp. 39-52. [In Italian]

[8] E. Demetrescu, Archaeological Stratigraphy as a formal language for virtual reconstruction. Theory and practice, in: Journal of Archaeological Science (2015) 57, pp. 42–55.
DOI: 10.1016/j.jas.2015.02.004

[9] A. Galeano, A. Sanseverino, S. Berto, E. Demetrescu, M. Limongiello, Extended BIM: a proposed workflow for the integration of the HBIM and EM approaches, Proc. of the 9th IMEKO TC4 Int. Conf. on Metrology for Archaeology and Cultural Heritage, Rome, Italy, October 19-21, 2023, pp. 115-120.
DOI: 10.21014/tc4-ARC-2023.023

[10] M. Lombardi, A Landscape Matrix: the EM tool for the analysis of the via Appia, Proc. of the 9th IMEKO TC4 Int. Conf. on Metrology for Archaeology and Cultural Heritage, Rome, Italy, October 19-21, 2023, pp. 677-682.
DOI: 10.21014/tc4-ARC-2023.126

[11] Enzo Cocca, PyArchInit4 by Luca Mandolesi & Enzo Cocca - QGIS plugin for archaeology, on Github. Online [Accessed 28 February 2024]
https://github.com/pyarchinit/pyarchinit

[12] C. Brandi, Teoria del restauro, 2nd ed. Einaudi, Torino, 1977. [In Italian]

[13] U. Baldini, Teoria del restauro e unita di metodologia. Nardini Editore, Firenze, 1982. [In Italian]
[14] G. Carbonara, Restauro architettonico. Principi e metodo. M. E. Architectural Book and Review, Roma, 2012. [In Italian]
[15] R. Parenti, Le strutture murarie: problemi di metodo e prospettive di ricerca, in Il progetto Montarrenti (SI). Relazione preliminare 1982. Archeologia Medievale, 10 (1983), pp. 417-437. [In Italian]
[16] T. Mannoni, Modi di fare storia con l'archeologia: variazioni sul tema di Andrea Carandini, Archeologia Medievale. 20 (1993), pp. 561-568. [In Italian]
[17] G. P. Brogiolo, Prospettive per l'archeologia dell'architettura, Archeologia dell'Architettura (1996) 1, pp. 11-16. [In Italian]
[18] G. Cagnoni, La documentazione del degrado e del dissesto nell'analisi stratigrafica degli elevati, Archeologia dell'Architettura (1996) 1, pp. 65-70. [In Italian]
[19] T. Mannoni, Qualsiasi degrado fa parte della storia dell'edificio, in: Dal sito archeologico alla archeologia del costruito. Proc. of the 34th Convegno SBC, Bressanone, Italy, 3-6 July 1996, Edizione Arcadia ricerche, Marghera Venezia, 1996, ISBN 978-88-95409-00-9, pp. 1-10. [In Italian]
[20] M. Radanovic, K. Khoshelham, C. Fraser, A platform for multilayered documentation of cultural heritage, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, V-4 (2021), 24.
DOI: 10.5194/isprs-annals-V-4-2021-9-2021
[21] G. Leonardi, C. Balista, Linee di approccio al deposito archeologico, in: Processi formativi della trasformazione archeologica. G. Leonardi (editor) Padova 1992. pp. 75–99. [In Italian]
[22] M. Asciutti, L'umidità come traccia storica: la torre sud ovest del complesso monumentale dei Ss. Quattro Coronati in Roma, in: RICerca/REStauro. Conoscenza dell'edificio: casi-studio, 2B. Quasar, Roma, 2017, pp. 512–523. [In Italian]
[23] F. Doglioni, Stratigrafia e restauro. Lint, Triste, 1997, ISBN 8881900181. [In Italian]
[24] F. Doglioni, Nel restauro: progetti per le architetture del passato, Marsilio, Venezia, 2008. [In Italian]
[25] F. Doglioni, Leggibilità della costruzione, percorsi di ricerca stratigrafica e restauro. Archeologia dell'Architettura (2010) 15, pp. 65-79. [In Italian]
[26] E. Demetrescu, D. Ferdani, From Field Archaeology to Virtual Reconstruction: A Five Steps Method Using the Extended Matrix, Applied Sciences 11 (2021) 11. Online [Accessed 29 June 2023] http://www.extendedmatrix.org
[27] B. P. Torsello, Scritture di pietra, in: Stratigrafia e restauro. Tra conoscenza e conservazione dell'architettura. F. Doglioni (editor) Lint, Trieste, 1997. ISBN 8881900181. [In Italian]
[28] C. Arcolao, La diagnosi nel restauro architettonico. Tecniche, procedure, protocolli. Marsilio, Venezia, 2008. ISBN 8831791788. [In Italian]
[29] Commissione NorMaL, UNI 11182:2006, Materiali lapidei naturali ed artificiali. Descrizione della forma di alterazione - Termini e definizioni, 2006. Online [Accessed 28 February 2024] [In Italian]
https://store.uni.com/uni-11182-2006
[30] V. Vergès-Belmin, ICOMOS-ISCS: Illustrated glossary on stone deterioration patterns/Glossaire illustré sur les formes d'altération de la pierre, english-french version, 15, ICOMOS, Paris, 2008
[31] Carta italiana del Restauro. Ministero della Pubblica Istruzione, Circolare no. 117, 6 aprile 1972. [In Italian]
[32] Emanuel Demetrescu, Extended Matrix 3D tools (EMTools), on Github. Online [Accessed 29 June 2023]
https://github.com/zalmoxes-laran/EM-blender-tools
[33] Emanuel Demetrescu, 3D-survey-collection, on Github. Online [Accessed 29 June 2023]
https://github.com/zalmoxes-laran/3D-survey-collection
[34] The Scene Baker, Interactive 3D tools & services by VHLab – CNR ISPC. Online [Accessed 29 June 2023]
http://osiris.itabc.cnr.it/scenebaker/index.php/projects/emviq/
[35] Emanuel Demetrescu, Extended Matrix official repository, on Github. Online [Accessed 28 February 2014]
https://github.com/zalmoxes-laran/ExtendedMatrix
[36] #SegniArcheologia. Guida interattiva alla città. F. Colaiacomo, E. Demetrescu, M. Martuscelli (editors) Segni, 2022. [In Italian]
[37] CNR ISPC, #SegniArcheologia. Guida interattiva alla città. Online [Accessed 29 June 2023]
https://www.segniarcheologia.it
[38] E. Demetrescu, A. Averini, M. Martuscelli, E. Valletta, G. Ferrazza, A. Palombini, E. Scopinaro. (2022). Segni (RM): Acropoli. Rilievo fotogrammetrico. V. 1, Data set, Zenodo. . [In Italian]
DOI: 10.5281/zenodo.7463167
[39] F. M. Cifarelli, Il tempio di Giunone Moneta sull'acropoli di Segni. L'Erma di Bretchneider, Roma, 2003. [In Italian]
[40] D. Ronchi, M. Limongiello, E. Demetrescu, D. Ferdani, Multispectral UAV Data and GPR Survey for Archeological Anomaly Detection Supporting 3D Reconstruction, Sensors (2023) 5, 2769.
DOI: 10.3390/s23052769