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# 3D Research Challenges in Cultural Heritage IV

## Risk Prevention and Monitoring Methods

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Marinos Ioannides · Giovanni Issini ·
Daniel Oliveira
Editors

# 3D Research Challenges in Cultural Heritage IV

## Risk Prevention and Monitoring Methods

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# Preface

In an increasingly fragile world, cultural heritage faces constant threats – from catastrophic earthquakes and environmental disasters to armed conflicts and the accelerating impact of climate change. Across the Middle East, Africa, Eastern Europe, and other vulnerable regions, historic buildings, monuments, and artifacts are disappearing at alarming rates. In response, the convergence of **3D digitization, structural analysis**, and **participatory technologies** is redefining how we protect, restore, and reimagine our shared heritage.

This volume issue brings together leading-edge research and multidisciplinary practices demonstrating how **digital tools** – from 3D scanning and photogrammetry to HBIM (Heritage Building Information Modeling), Digital Twins, and Extended Reality (XR) – are transforming the way we understand and care for tangible heritage. These technologies not only record the physical form and material conditions of sites but also enable simulations of deterioration, design interventions, and reconstruct with accuracy and empathy.

Crucially, **structural analysis integrated within 3D models** offers predictive insights into the stability and longevity of heritage sites. By analyzing stress factors, material decay, and environmental risks, especially in earthquake-prone areas, we can move from reactive conservation to **preventive preservation**– mitigating potential damage and informing smarter, safer restoration practices.

A central theme of this issue is the recognition of post-disaster restoration – not merely as a technical operation but as a **living cultural process**. In the aftermath of earthquakes, restoration and reconstruction efforts often provide opportunities for local communities to **recover, reinterpret, and renew their cultural identity**. The act of rebuilding fosters a collective narrative of resilience and pride. To support this process, there is a growing need to define tools and methodologies that enable **public access and cultural use of damaged sites during their restoration**, allowing them to remain part of everyday life even amid repair. Making the **scientific and technical content of restoration accessible** to broader audiences through innovative visualizations, interactive platforms, and storytelling is essential. Digital tools should not only serve experts but also empower the public, allowing for **participation both on-site and remotely via the web**. Furthermore, the integration and publication of restoration data in accessible formats can serve multiple audience groups – including local communities, researchers, policymakers, and educators. This participatory model also calls for the **training of cultural operators and restoration professionals** in effective communication and engagement methods, bridging the gap between expert knowledge and public understanding. Simultaneously, prioritizing **education for younger generations** is critical, fostering awareness of best practices in architectural conservation and inspiring future stewardship of cultural heritage.

In an era where digital and physical realities increasingly intertwine, 3D digitization is no longer a technical luxury - it is a **cultural imperative**. This volume advocates a holistic approach to heritage management, combining cutting-edge technology with local knowledge, risk analysis with creative reuse, and positioning the act of restoration as a bridge connecting the past, present, and future.

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# On the Use of HBIM for the Analysis of Historical Constructions: Technical and Semantic Interoperability for Different Aspects of the Structural Assessment

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**Abstract.** The rehabilitation of historical buildings has always had to deal with an innumerable amount of data, managed by stakeholders with different fields of expertise. Hence, it is characterized by long processes with high risk of losing information or repeating analyses and tests. Building Information Modelling (BIM) offers the potential to streamline these workflows and enhance the efficiency of the team. However, the adoption of BIM in the construction industry has been challenging, and it is particularly difficult to apply it to historical buildings. This book chapter outlines the major challenges in the implementation of BIM and examines the efforts being made by the scientific community to tailor this methodology to the unique needs of historical buildings, highlighting the benefits of using it. It will then discuss the efforts that have been undertaken to address these challenges and present the various approaches being used to more accurately represent heritage objects. Finally, examples will be provided of the various uses of Heritage BIM models, with a focus on the structural assessment of historical buildings.

**Keywords:** HBIM · Structural Analysis · Interoperability · Historical Buildings · Rehabilitation

## 1 Introduction

A major challenge in built heritage conservation lies in its inherently multidisciplinary nature, requiring the integration of historical, humanistic, and technical-scientific expertise to effectively assess and preserve historic buildings. Although there are various training and specialization courses available, it is uncommon to find professionals who possess expertise in all aspects of conservation. As a result, rehabilitation projects often become fragmented, involving multiple stakeholders who collect and interpret information separately. This fragmentation can lead to the loss and repetition of data between subsequent steps, especially when systems lack the capability to communicate effectively with one another.

In response to these challenges, the scientific community has increasingly focused on digitizing conservation processes over the past decade. While significant progress has


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been made, certain aspects remain difficult to accurately represent. One major issue is that some critical information—such as structural conditions and material degradation—is still primarily gathered through traditional methods like visual inspections, which digital tools have yet to fully replicate or integrate effectively. Beyond data acquisition challenges, material-specific limitations also pose difficulties. Unreinforced masonry and wood, common in historic structures, exhibit distinct characteristics that differ significantly from modern construction materials, making it challenging for many digital platforms to provide accurate structural simulations and assessments. Moreover, the use of various software applications throughout the rehabilitation process, often based on different programming languages, complicates communication between different stages of the project.

The advent of Building Information Modelling (BIM) has been a complete paradigm shift in the Architecture, Engineering, and Construction (AEC) industry. BIM is a process for creating and managing information throughout its whole life cycle [1]. Thus, it consists of central integrated design, modelling, and asset planning system that provides all stakeholders with a digital representation of the building. One of the key benefits of BIM is its compatibility with many of the technologies used in the digitalization sector. Initially, digitalization occurred in various areas of construction independently.

The possibility of employing BIM for the assessment and rehabilitation of historical buildings has been the centre of a large debate for a long. The first studies in this direction have been conducted in [2] where it is stated the convenience to use BIM for managing the complexity of the geometry of historic construction. Following this approach, Arayici further advocated for the integration of advanced survey techniques to enhance the accuracy and efficiency of the modelling process [3].

The acronym HBIM, standing for Historic-BIM (or, in some applications, Heritage-BIM), is currently widely used in this context. According to several sources [4, 5] it appears to have been coined in [6] to indicate a new approach to modelling historic buildings, supported by a library of reusable parametric objects. In the first stage, the major concern of the researchers involved in this area was the management of geometrical information, extremely complex due to the lack of standardization of heritage construction objects.

Nowadays, the original definition of the term HBIM represents only part of the potentiality of this tool, as crucial new aspects have taken over, such as alphanumeric information [7] data granularity [8, 9] process management [10], and simulations [11].

This chapter aims to address the challenges and potentiality in the use of BIM for historical constructions. The chapter is organized as follows. After this introduction, Sect. 2 will outline the principles of BIM methodology. Section 3 will examine the methodologies proposed by the scientific community to extend this technology to existing construction. Finally, the chapter will focus on the applications of Heritage BIM (HBIM) to the needs of historical constructions, highlighting the importance and challenges of structural analysis.

## 2 BIM Potentialities and Challenges

The transition from traditional to Building Information Modeling (BIM) methods, even for the design of new constructions, is ongoing and complex, largely due to a shortage of skilled personnel, lack of awareness and understanding of digital technologies, and the cost of equipment and software [12].

The BIM maturity map identifies five levels of BIM maturity based on an assessment of four BIM milestones: 1) content, 2) digitalization, 3) interoperability, and 4) collaboration [13]. Figure 1 illustrates this framework, which helps to progressively analyse the full potential of BIM and clarify common misconceptions. The four BIM milestones are discussed in details in the following sections.

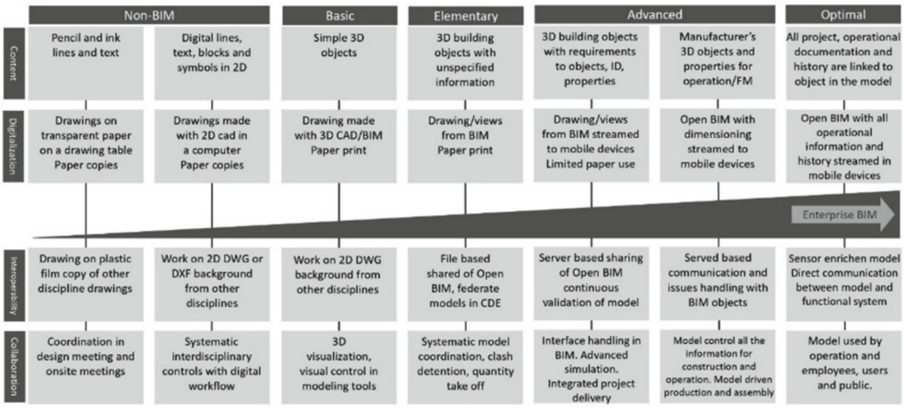


**Fig. 1.** BIM maturity map. Adapted from [13]

### 2.1 Content

One key characteristic that helps identify a BIM model is its focus on object-oriented modelling, in contrast to the entity-oriented modelling commonly used in CAD software [1]. This distinction highlights why the original definition of HBIM emphasized the use of a library of parametric objects. Objects are described by a set of geometrical and non-geometrical parameters (referred as '*alphanumerical*' in the BIM jargon), ideally expressed using a human and machine-readable language.

Advanced BIM maturity is achieved when the introduced data are based on specific requirements. In particular, ISO 23387 presented the concept of Product Data Template (PDT) defined as "a subset of this model, providing the concepts and relationships needed to describe information about construction objects" [14]. In the scope of built heritage, PDTs have been proposed by Barontini et al., for the inspection of historic masonry walls and the monitoring of structural cracks [7].

Beyond standardization, another crucial aspect is determining the appropriate timing for disseminating specific information. The concept of Level of Development (LOD) [15] was introduced with this aim. This framework specifies the geometrical and alphanumeric information required for five different design phases—LOD 100, LOD 200, LOD 300, LOD 350, and LOD 400. In this context, he importance of defining LOD specifically for heritage projects has already been recognized. For instance, Jordan-Palomar et al. [9] proposed a protocol named "BIMLegacy" to manage heritage building information using HBIM. They raised an important question about defining LOD for built heritage, highlighting both the advantages of using BIM to document the different construction phases of historical buildings and the challenges of determining *a priori* the amount of information that can be collected at each project stage.

A more structured approach to information management has been established through the EN ISO 19650 series [16–19]. This standard specifies the necessity of defining the so-called "Exchange Information Requirements" (EIR) and the "BIM Execution Plan" (BEP) to ensure that the appropriate level of information is delivered at each project milestone. Considering that a BIM project works "for appointment", it is needed to propose an EIR every time that there is an appointment, to establish the requirements that are needed for that specific stage of the project. This concerns the stakeholder involved, their training and knowledge, but also the information to include in the model.

The *"Level of Information Need"* [14] was introduced to clearly establish how information should be structured and stored. Specifically, the information required in the model is determined by the purpose of the model itself. According to this approach, the project is divided into different delivery milestones, with objects being associated with specific geometric and alphanumeric information, as well as the required documentation, based on the model's intended use. A key feature of this framework is that different purposes can coexist within the same delivery milestones. In a previous work, the author proposed a Level of Information Need framework for the seismic assessment of historic masonry buildings, specifically tailored to the finite element analysis milestone [20].

### 2.2 Digitalisation

While it is true that the digitalization process reduces reliance on traditional "paper" workflows, this perspective is somewhat reductive. The digital revolution, as envisioned by the European Committee, is driven by the integration of multiple technologies aimed at significantly enhancing the construction and management processes. Currently, BIM has a significant level of integration with other emerging tools, especially data acquisition technologies [12].

Among these, 3D laser scanning and drones [21] are powerful tools for capturing the geometry and visual appearance of buildings, while sensors [22] and the Internet of Things (IoT) [23] allow to constantly receive data and update the model. As a result, the concept of digital twins has emerged, referring to an "as-is" or "live" three-dimensional representation of an existing building [24, 25] with high potentiality in the context of maintenance [26] and decision-making [27].

Digital twins have proven to be highly effective in the management of existing buildings and complex heritage structures, as evidenced by the growing interest of the scientific community in this field [28–30].

### 2.3 Interoperability

Interoperability is the "ability of two or more systems or components to exchange information and to use the information that has been exchanged" [31] and allows the integration of different technologies and sources.

In the field of built heritage, the primary focus is on semantic and technical interoperability, which are crucial for product data exchange. Semantic interoperability ensures that the meaning of the data is preserved during the exchange of information, while technical interoperability refers to the physical connection between the systems [32].

The challenge of product data exchange has drawn attention in the AEC industry since the 1950s, when *ad-hoc solutions* have been used to exchange information between software [33]. A significant milestone was reached with the standardization of the STEP [34], which introduced a universal framework for data exchange across multiple industries, including AEC/FM. In 1994, the Industry Foundation Classes (IFC) standard—based on the EXPRESS language—was introduced by the International Alliance for Interoperability (now buildingSMART) to cover all vital building information throughout its lifecycle [33].

The IFC standard plays a critical role in ensuring interoperability between systems. However, as noted in [32] interoperability is now facing the challenges of passing from 'information' to 'knowledge' management. This transition presents significant challenges, as the earliest product data exchange methods were introduced when many of today's advanced technologies were still in their infancy. As a result, the current IFC schema is becoming insufficient for integrating emerging digital systems.

On the other hand, the goal is no longer just to transfer information between systems but to provide *knowledge* about specific sectors. However, IFC is increasingly seen as lacking the necessary semantic depth to meet this objective [35].

The EXPRESS language, introduced in 1994, was primarily intended for the design of new constructions [33], and may not be fully suited for historic construction. To add undefined properties or types, specific placeholders and property sets can be used (IFCProxy) and (IFCPropertySet). However, these types of descriptions are semantically poor [36] and the process of officially integrating elements in IFC standards takes a very long time [37].

Currently, extended semantic modelling is often associated with the 'linked data approach,' which facilitates structured data representation and interoperability across domains. Web Ontology Languages have been explored as a means to enhance IFC-based data exchange and address some of its limitations [38, 39]. The interoperability between IFC and OWL (Web Ontology Language) has been proposed in [39] and developed by [40] with the IfcOWL conversion pattern. Nevertheless, its considerable length and complexity make it difficult to apply effectively in real-world scenarios. Consequently, more compact ontologies have been introduced as alternatives for representing construction instances within the semantic web [41]. Examples of semantic modelling in heritage research will be explored in the in Sect. 3.

### 2.4 Collaboration

A comprehensive BIM model, linked to digitalized documentation related to all involved systems, enables the coordination of operations throughout the entire building lifecycle

[42]. As BIM collaboration involves multiple stakeholders managing diverse types of information, a structured and centralized system is essential for ensuring efficient data exchange and coordination. To address this, the concept of a Common Data Environment (CDE) has emerged as a key solution.

The term CDE refers to the use of cloud technology to create a project or central space to handle integral model-based project management, and it is a key component of the EN ISO 19650. A CDE facilitates storing and managing various project-related data, including BIM data, documents, and other relevant information. The scope is to support information management across all project phases: planning, design, construction, operation, and maintenance.

Several BIM protocols outline the definition of a CDE by establishing the standards to be followed [43]. These standards not only address naming conventions and the expected content to be delivered, but they also specify the responsibilities, liabilities, and limitations of each project member. The benefits of using a CDE in the management of built heritage have been recently explored in [4, 44] in relation to handling multidisciplinary information for evaluating the sustainability of restoration projects.

## 3 Extending BIM Methodology to Cultural Heritage Buildings

### 3.1 Geometric Data Acquisition and Modelling Techniques

Due to the complex geometry of historic buildings and the unique characteristics of each structure, here has been a strong emphasis on geometric modelling in the advancement of HBIM. Historically, researchers have focused on developing abacuses and manuals to characterize common construction components. However, these resources provide only idealized representations of architectural elements, lacking the geometric accuracy needed to capture real-world variations, deformations, and material irregularities found in historic structures [45]. As a result, BIM researchers have sought alternative strategies to generate more representative parametric objects [6].

To this end, the SCAN-to-BIM framework has been widely adopted to achieve more accurate digital representations of heritage structures. SCAN-to-BIM is a process that converts point cloud data from laser scanning or photogrammetry into BIM [10, 46–54].

Terrestrial Laser Scanning (TLS) is often used for capturing precise geometric data. Photogrammetry offers a lower-cost alternative to TLS but is generally less precise. Videogrammetry, which requires minimal human intervention during data capture, has even lower precision and demands greater computational resources.

While various techniques exist for acquiring spatial data, their integration into BIM environments follows two distinct approaches: forward modelling and reverse modelling [55].

In forward modelling, historical documentation serves as the starting point for defining objects. Parametric components are initially represented according to the rules outlined in manuals. A subsequent process of mapping the 3D point cloud space is then undertaken to enhance accuracy and capture the object's actual state, including any damage, deformations, or specific details. This traditional approach was first implemented in [6, 50] and required human interpretation to integrate both types of data.

In contrast, reverse modelling directly generates parametric objects within the BIM platform using information from the point cloud, typically acquired via terrestrial laser scanners. Automatic or semi-automatic algorithms have been developed for this purpose and have proven effective for relatively simple geometries, such as planar walls and floors. However, human intervention remains necessary. With this scope, in [52] it is presented a plugin designed to facilitate the integration of BIM with point cloud data. Figure Fig. 2 provides a comparative overview of forward and backward modelling approaches within the SCAN-to-BIM framework, highlighting their key steps and methodological differences.

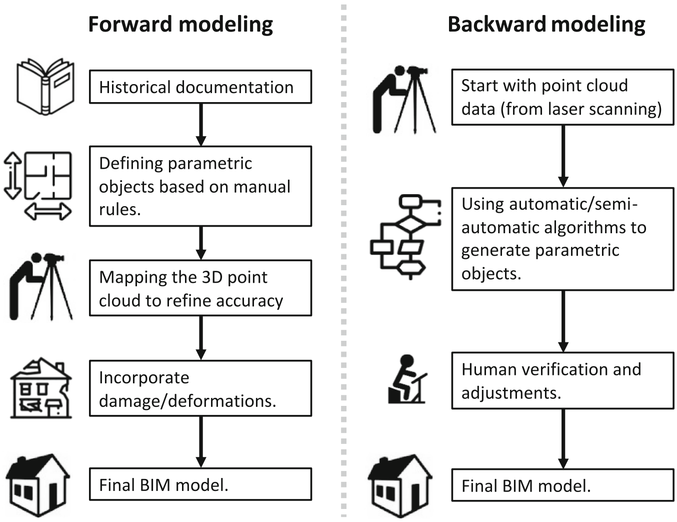


**Fig. 2.** Forward modelling vs backward modelling

A notable methodological approach was proposed in [4] and [56]. These studies compares a theoretical model based on classical architectural principles with an "*as-is*" model from laser scanning data, highlighting the latter's superior accuracy. It emphasizes precise deformation acquisition using laser scanners, specifically in portico-type structures. The findings reveal that theoretical models often miss significant structural deformations.

The transition from point clouds to three-dimensional BIM geometry remains a complex aspect of the modelling process. Regardless of whether the forward or reverse modelling approach is used, the transition from an imperfect point-based geometry to an idealized representation—such as Boundary Representation (BRep) or Constructive Solid Geometry (CSG)—is essential.

To address this challenge, the literature identifies three primary approaches for processing point cloud data into BIM-compatible geometry: a) Patch adaptation from mesh modelling [57]; b) NURBS-based reverse modelling [47, 48, 58] c) Slicing methods for geometry simplifications [58–60].

The following sections provide a detailed discussion of these methods. In particular, the studies presented share a common objective: utilizing the BIM model specifically for structural analysis. The examples demonstrate that, even after creating a BIM model consistent with its fundamental principles, additional challenges arise in ensuring interoperability between the BIM model and the structural model.

In all analyzed cases, the structural modeling approach is based on solid finite elements, which are particularly suitable for historic masonry buildings. While most commercial BIM software allows for structural modeling, it is typically limited to beam or shell elements. For this reason, applying the BIM-to-FEM approach to historic buildings, especially unreinforced masonry structures—requires additional interoperability steps with FEM software capable of solid modeling.

**Patch-Adaptation from Mesh**

Patch adaptation refers to fitting and refining discrete surface segments (patches) within a mesh to represent complex geometries accurately. This method is commonly used in SCAN-to-BIM workflows to convert irregular point cloud data into structured parametric models. Bassier et al. [57] proposed an application of this method to timber structures. In their work, this method, the point cloud data is processed using Reshaper software, which employs a coarse-to-fine meshing strategy. The generated mesh is subsequently transferred to SolidWorks [61] to derive parametric objects. Manual refinement is necessary to ensure geometric consistency and solid integrity, essential for FEM. The finalized parametric objects are then exported to the BIM environment via the IFC format, while a parallel workflow enables their integration into FEM analysis using Ansys [62].

**NURBS-Based Reverse Modelling**

Non-Uniform Rational B-Splines (NURBS) are widely recognized in international standards such as STEP and serve as powerful tools for geometric modelling. In NURBS-based reverse modelling, specialized reverse engineering software converts point cloud data into a mesh, which is subsequently transformed into a NURBS-based solid, as proposed in [47, 48, 53].

Banfi [47] introduced the concept of Grade of Generation (GoG) in BIM modelling, highlighting that conventional geometry generation methods—such as extrusion, profile editing, or profile extension—are insufficient for accurately representing historic structures. Building upon this, two advanced methods are introduced to enhance the generation of complex geometries: 1) NURBS from a wireframe, which constructs surfaces by interpolating curves; 2) NURBS from control points, which generates surfaces based on a set of predefined control vertices.

Figure 3 illustrates this workflow, where terrestrial laser scanning data is processed into NURBS surfaces using the two mentioned methods: 3D wireframe or simple set of points. The resulting surfaces are then refined by adding thickness, ultimately creating a BIM object suitable for heritage documentation and structural analysis.

The NURBS-based reverse modelling approach presents certain limitations when dealing with highly complex geometries. A major challenge is thickness generation, achieved through an offset operation that requires new mathematical functions to ensure consistency. Despite this, self-intersections and geometric irregularities often persist. This issue becomes particularly critical when transitioning from the BIM model to the

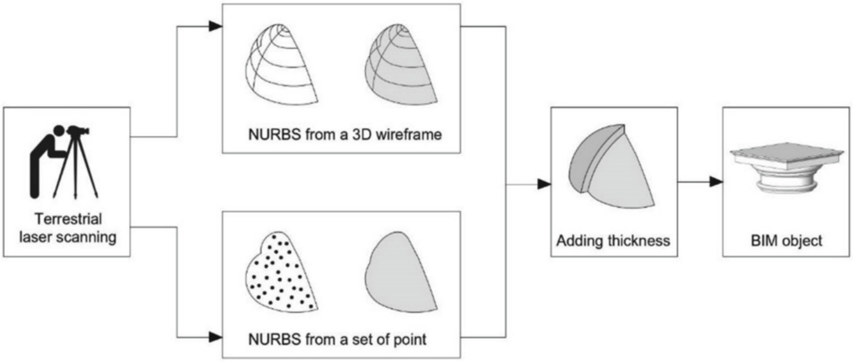


**Fig. 3.** Workflow of NURBS-based reverse modelling: Terrestrial laser scanning data is processed into NURBS surfaces using two methods— (1) from a 3D wireframe and (2) from a set of points. The generated surfaces are then refined by adding thickness to create a BIM object

FEM model, as implemented in Midas software. Several simplifications and remeshing operations are required to generate a finite element mesh suitable for structural analysis.

**Slicing Method for Geometry Simplification**

The slicing method processes point cloud data into 2D sections, simplifying complex geometries for structural analysis and finite element modelling (FEM). This approach extracts planar slices along the Z-axis, defining internal and external profiles, which are then stacked to reconstruct the volume. This methodology has proven particularly effective for structural analysis, as it maintains an adequate level of detail for solid analysis while ensuring that the geometry remains manageable, reducing the need for extensive post-processing, simplification, and remeshing.

In the literature, at least two applications of this method can be identified. Castellazzi et al. [60] use planar slicing to generate voxel elements, each assigned mechanical properties. This framework has been applied not only in FEM also in Discrete Element Modelling (DEM), demonstrating its versatility for different structural analysis approaches.

A second implementation was developed by Rolin et al. [61] for the structural analysis of a Gothic-style church. In this approach, point cloud data was extracted every 20 cm, creating planar sections along the Z-axis. Figure 4 illustrates the slicing process applied to a historic building for structural analysis. The leftmost image represents the raw point cloud data, which is then processed into structured slices along the Z-axis to generate cross-sectional profiles. The middle image shows the resulting structured slices, providing a simplified geometric representation. Finally, the rightmost image represents a further refined version, highlighting key architectural features while reducing unnecessary complexity. Tetrahedral four-node elements were used for the FEM analysis.

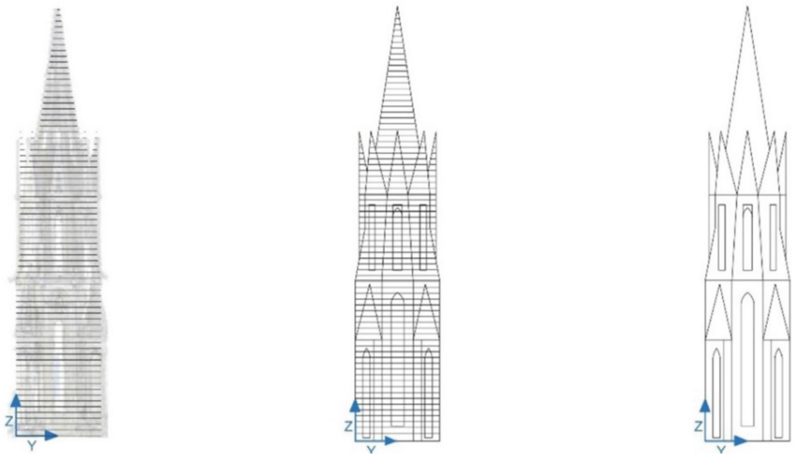

**Fig. 4.** Slicing process applied to a historic building: (Left) Point cloud representation, (Middle) Structured slicing along the Z-axis, (Right) Simplified geometric model for structural analysis [adapted from [60]].

### 3.2 Semantic Enrichment of HBIM Models

Managing the complex geometry of historic constructions in BIM is only one part of the challenge; equally important is the ability to enrich these models with structured, semantic information. Beyond geometric accuracy, HBIM requires the integration of alphanumeric data to enhance documentation, analysis, and interoperability. The challenge extends beyond simply enriching the BIM model with alphanumeric parameters. A fundamental issue lies in the substantial differences between new and existing structures, which require different class hierarchies than those available in proprietary software or open formats.

In [8] it is discussed that BIM should not serve merely as a digital representation of a building but as a collaborative tool that fosters interdisciplinary synergy in studying architectural heritage. Figure Fig. 5, adapted from [63] illustrates the conceptual framework for HBIM as a multidisciplinary tool rather than a mere geometric representation. The left diagram presents a redefined spatial structure, introducing intangible and removable geometric elements such as "space" (intangible objects) and "face" (patina) alongside traditional construction and load-bearing elements. This model recognizes that historic buildings are not static but evolve over time, requiring a more dynamic representation (as discussed in [63]). The right diagram depicts the interdisciplinary integration of HBIM within a shared database environment. Graphical and alphanumerical documentation serves as the primary input, feeding into digital tools such as BIM and GIS, which structure and manage the data. The central database connects various disciplines (e.g., historiography, archaeology, chemistry, architecture, and structural analysis), ensuring a collaborative approach to heritage studies. The final outputs include research, dissemination, management, and project development, reinforcing BIM's role as an information hub rather than just a geometric model.

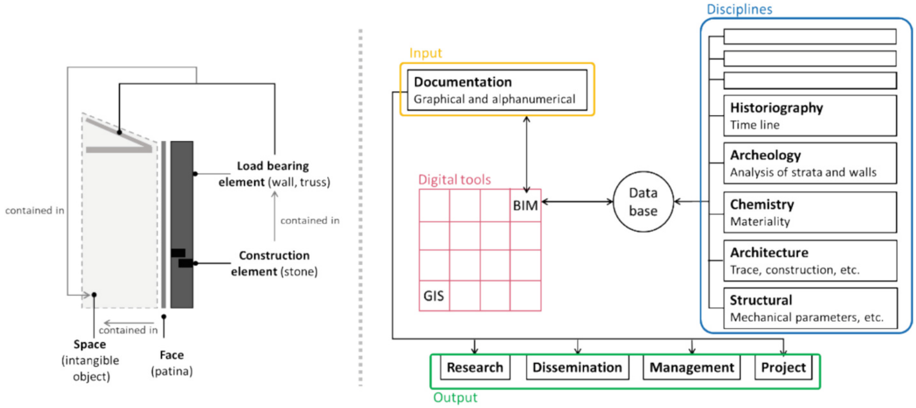


**Fig. 5.** HBIM as a multidisciplinary information hub: (Left) Representation of different spatial elements, including intangible and removable components. (Right) Framework illustrating the integration of BIM with a shared database to facilitate collaboration across historiography, archaeology, chemistry, architecture, and structural analysis (adapted from [63]).

Various authors have addressed these needs by leveraging external linked databases and semantic web languages to enhance data integration and interoperability. For instance, Simeone et al. [64]developed a specific ontology that effectively breaks down the structure of architectural order, such as dividing a column into its components: base, shaft, and capital. Additionally, other critical aspects are represented, including the type of survey used, current legislation, and information about different construction periods, all presented through well-structured metadata. Building on this approach, Garozzo et al. [65] introduced CulTO, an ontology tailored for religious heritage, which defines physical objects and their associated properties. Similar to Simeone et al., this ontology establishes a hierarchical breakdown of architectural elements, reinforcing a standardized classification framework.

Quattrini et al. [10] expanded this concept by classifying church elements not only as physical components but also in relation to intangible spatial structures, such as the nave, apse, and vestibule. Figure Fig. 6, adapted from [10] presents a hierarchical semantic structure for representing buildings and their components in a linked data framework. The ontology is organized into classes, subclasses, relationships, and properties, visually distinguishing between different data types. At the top level, the “Building” class is connected to “Building Components”, which are further divided into subclasses representing specific architectural elements (e.g., Nave, Apse, Dome, Vestibule, Column, Wall, Window). These subclasses inherit properties and relationships from their parent class. The ontology also defines data relationships, where a building is part of a broader system, and it is comprised of various building elements. Each building element contains specific data properties, such as identity data, graphical representations, materials, analysis results, and web links. These properties support semantic interoperability, enabling enriched information retrieval and data integration.

Moraitou et al. [66] collected and described various semantic models proposed in the last decade for the conservation and restoration of built heritage, showing that the

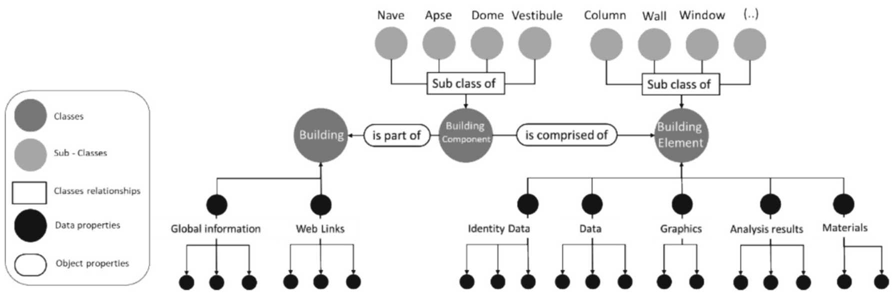


**Fig. 6.** Semantic structure of a building ontology: The hierarchy classifies buildings, components, and elements, defining their relationships and associated data properties to facilitate structured knowledge representation and interoperability (adapted from [10]).

interest has been towards 1) Monument damage information system, as developed in the MONDIS project [67], proposing an interesting tool for import, editing, processing visualizing the data from the core ontology; 2) Non-destructive testing techniques, developed starting from the CIDOC-CRM ontology [68]; 3) Annotation of the degradation phenomena on 3D reconstructions, which has been done considering the ICOMOS illustrated dictionary for degradation phenomena in the stones and integrating the CIDOC CRM ontology [69]; 4) Introducing ontology on a framework for conservation processes integrated with BIM using a *semantic bridge* between Protégé and Revit, and considering the CIDOC CRM as a base ontology [70]; 5) Digitalization of "risk maps" of the MiBAC recommendation for historic centers [70–72].

In the realm of structural analysis, a different approach is required to integrate geometric and material data with engineering assessments. With is aim, the author introduced a methodology employing linked data and semantic web rule languages to enhance the seismic analysis of unreinforced masonry structures. They developed two complementary ontologies: the Historic Masonry Ontology, which defines the mechanical properties of masonry materials, and the Failure Masonry Ontology, which identifies probable collapse modes during earthquakes [73, 74].

## 3.3 HBIM to GIS Integration

For the sake of completeness, a brief overview of HBIM-GIS integration is provided, as it remains one of the most challenging aspects of the BIM framework. In particular, the interoperability between GIS and BIM technologies, or better EXPRESS to CityGML, can be semantically solved by employing ontologies based on the semantic web languages. Liu et al. [75] pointed out that the use of a "reference ontology" that is common to several domains is a sort of bridge between the two languages. These efforts suggested that the management of data through a well-structured ontology based on semantic web technologies is the right approach to support interoperability between fields.

The major concerns that the investigators are now facing in the development of HBIM to GIS frameworks are the same as BIM to GIS ones, as well as the general HBIM worries. Dore and Murphy, while introducing the term "HBIM" in 2012, questioned the integration of this new approach and GIS frameworks, pointing out the possibility of using a large amount of information stored in HBIM to support planning, disaster management, and other specific uses implemented in GIS. Issues are related to the different structures of EXPRESS language and CityGML language. In the former, the entities are referred to each other by line number. In the latter, the relationships are based on XML. Additional challenges arise from the transition from project-based information management, as outlined in ISO19650 (BIM), to a system based on level of detail (CityGML), which dictates the level of geometric and semantic complexity required for a particular application of the 3D city model. This transition presents a significant obstacle in the context of the BIM-GIS framework and is particularly problematic in the case of historical structures, as the current classes and features within CityGML do not adequately represent the characteristics of such objects.

The question of using BIM-HBIM-GIS frameworks for multi-scale risk evaluation has been critically discussed in Eudave and Ferreira [76], which proposed a comprehensive workflow with the scope of defining which tool must be used in each specific moment of the assessment. In their framework, they pointed out the importance of this tool for risk assessment of city centers. Cardinali et al. [77, 78] proposed a multi-scale approach for seismic vulnerability assessment of historic centers characterized by compounds structures in masonry, using GIS and HBIM, but without a real integration between the tools. Saccucci [79] investigated the use of HBIM for the structural assessment of complex masonry historic dwellings, supported by a GIS-based repository to extract information about the seismic risk in Italy.

## 4 Expanding the Role of HBIM in Structural Analysis and Multi-disciplinary Assessments

The previous section provided insights into why HBIM research has prioritized certain aspects over others. Key challenges include geometry management, alphanumeric data integration, and interoperability between different systems. Additionally, much of the scientific literature explores how BIM can support problem-solving within the rehabilitation process. One of the most extensively studied areas is structural analysis, given the unique challenges of historic buildings, particularly those constructed using traditional masonry techniques, which do not conform to standard calculation models used for modern structures. As a result, technical interoperability has become a central focus for researchers. In this context, the SCAN-to-BIM-to-FEM framework for continuum finite element modeling has gained significant traction [48, 60, 80, 81]. Leonardi et al. [20] proposed an automated BIM-to-FEM methodology, entirely based on open formats and tools, applied to a case study involving a group of unreinforced masonry historic buildings.

Beyond continuum modelling, HBIM has also been explored for kinematic analysis. Saccucci [82] proposed a workflow for masonry aggregates, leveraging HBIM data to assess structural stability. Further extending this research, Pelliccio et al. [83] employed mono-dimensional finite elements for a global structural evaluation of a case study. Their work highlights how HBIM can facilitate multiple types of analysis, including structural performance, wind exposure, and solar irradiation, demonstrating the advantage of integrating various disciplines within a unified model.

A similar multi-scalar approach was proposed by Gigliarelli et al. [11], who raised the issue of integrating analyses across urban and building scales to ensure compliance with rehabilitation project requirements. Several studies have emphasized the role of HBIM in energy efficiency analysis, particularly for sustainable retrofitting [11] and its potential in facility management [84, 85]. These frameworks demonstrate the versatility of HBIM, showing how it enables cross-disciplinary collaboration and decision-making within a single environment.

In addition to kinematic and multi-disciplinary studies, Quattrini et al. [10]proposed an alternative approach to structural assessment, focusing on empirical evaluation of out-of-plane collapse mechanisms. Meanwhile, Calvano et al. [86] explored the use of visual programming to integrate the Masonry Quality Index [87] into HBIM, improving the assessment of masonry structural integrity.

Another critical area of research is the documentation of deformation and damage within historic buildings. In [88] it is proposed using HBIM to acquire and compare deformations by juxtaposing ideal and real geometries, captured through advanced survey techniques. Similarly, Maliverni et al. [89] employed HBIM for damage recording, developing a 3D "decay map" of structural deterioration. Mol et al. [90] applied a similar approach to timber structures, while Barontini et al. [7] proposed a methodology for assessing the state of conservation, focusing on embedding alphanumeric data within the model.

## 5 Conclusions

The introduction of BIM has significantly transformed the way construction projects are designed and managed, enhancing data sharing and digitization. However, this revolution has also impacted the assessment of existing structures, including historic buildings. Over the past decade, researchers have explored how to adapt BIM methodologies to the heritage-built environment, addressing key challenges such as handling complex geometries, ensuring software interoperability, and managing alphanumeric data. One of the primary difficulties has been defining appropriate parameters for historical building components, as conventional BIM object libraries are tailored to modern construction. To tackle this issue, advanced survey tools and SCAN-to-BIM frameworks have been employed to generate more accurate representations. Nonetheless, the Industry Foundation Classes (IFC) scheme has proven insufficiently flexible for existing structures, requiring alternative breakdown structures and parameter definitions. The linked data approach, leveraging semantic web languages, has emerged as a promising solution to enhance data structuring and integration. Another critical aspect of interoperability is BIM-GIS integration, which enables multi-scale management of building-related information.

Beyond documentation and data structuring, HBIM plays a crucial role in structural analysis, a field that presents its own set of challenges due to the unique characteristics of historic materials and construction techniques. The scientific community has made significant progress in bridging structural analysis with other assessment methodologies, yet the establishment of standardized frameworks and ontological dictionaries remains an ongoing challenge. However, the growing interest and continued research efforts in this domain indicate that these challenges will be actively addressed, paving the way for more integrated and effective solutions for heritage conservation and analysis.

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# The Key Role of Structural Health Monitoring as a Control Tool in the Post-earthquake Recovery Phase of Damaged Heritage Buildings: The Case Study of "Collegiata di Santa Maria" in Visso, Italy

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**Abstract.** This chapter introduces the subject of structural health monitoring (SHM) and discusses its important role in the post-earthquake assessment of damaged built heritage. The first part of the chapter describes the SHM operational workflow and provides practical advices for each of the different stages composing the procedure, while the second part exemplifies a real case-study application. The investigated structure is a cultural heritage building severely damaged by the Central Italy seismic sequence of 2016–2017. The steps leading to the design of the SHM system architecture installed in the building and to the definition of the most appropriate sensor network topology are presented, along with a preliminary insight into selected results that will act as comparative baseline information throughout the post-earthquake recovery phase of the monitored structure until completion of the restoration process.

**Keywords:** Seismic Damage · Static Monitoring · Dynamic Monitoring · Historical Buildings · Preventive Conservation · Post-earthquake Reconstruction

## 1 Introduction

Architectural heritage represents the living expression of the cultural identity and diversity of modern societies. Beyond the historical significance and aesthetic value, built cultural heritage contributes to the touristic attractiveness of countries and regions, yielding important benefits in terms of gross domestic product. Assuring its protection, conservation and transmission to future generations is a cultural, societal, and economic requirement [1].


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The condition assessment of heritage buildings assumes great importance in this context, yet it is extremely challenging. The complexity of ancient geometries, the intrinsic variability of adopted materials, the use of local and non-codified construction techniques, and the limited knowledge about past events and ex-post retrofitting interventions, contribute to increasing uncertainties about the actual performance of these unconventional structures, especially under non-ordinary loading conditions [2–4]. Visual inspection procedures are fundamental to shed light on the current state of the system but, in most cases, they result insufficient for safety evaluation, as structural defects can lie beneath the surface of the building. To enhance the level of knowledge and elaborate a correct diagnosis of the structure, a multidisciplinary and multilevel approach combining critical historical analysis and in situ diagnostic investigations must be adopted [5–7].

Among the restricted number of diagnostic techniques applicable for the experimental characterization of buildings with historical value, Structural Health Monitoring (SHM) has been proved particularly effective, allowing to trace the system's in-service behaviour on a regular basis without resorting to any invasive technique and detaining a key role both as a diagnosis and control tool [8]. As a diagnosis tool, SHM enables to obtain baseline information on the structural health, to analyse the impact of operational and environmental effects, to timely identify anomalous trends and hidden damages as well as to assess the need for strengthening interventions and to calibrate realistic numerical models for advanced structural analyses and safety evaluations [9–13]. As a control tool, SHM is primarily employed before/during/after the execution of consolidation works and retrofitting interventions to compare the evolution of the structural response with the aim of verifying the effectiveness of the adopted remedial measures and quantifying their impact on the overall structural performance [8].

Given its potential for real time structural assessment and early warning in case of damage, SHM can also play a crucial part in the protection of heritage buildings located in earthquake-prone areas, allowing to support civil protection activities during rescue operations and to keep under control the behaviour of damaged structures in the post-earthquake recovery phase, assisting in the prioritization of restoration actions [14–17]. As very often resources allocated for reconstruction and conservation measures are limited, it is essential to set priorities in order to optimise available funding. The implementation of SHM-based strategies can help the local governance define priority-based reconstruction plans and cost-effective restoration actions, supporting the wise use of national and supranational resources for the long-term protection of built cultural heritage.

Due to the afore-mentioned reasons, the employment of monitoring tools for preventive conservation purposes has reached a wide consensus within the scientific community in the last years. Trying to mention a few emblematic applications of SHM to heritage structures, the following examples can be referred: the long-term monitoring for condition-based structural maintenance of the Milan Cathedral [18]; the static SHM of the church of the Sant Cugat monastery in Spain [19]; the static and dynamic monitoring for post-intervention assessment of the Saint Torcato church [8] and of the Mogadouro clocktower [20] in Portugal; the SHM for evaluation of earthquake-induced effects on the Saint Peter bell tower in Perugia, Italy [21]; the long-term monitoring of the Consoli

Palace in Gubbio [22] and the one of the San Frediano bell tower in Lucca [23], both in Italy, carried out for assessing the influence of temperature effects on the structural behaviour. Although literature is rich in successful applications of SHM, managers and building owners continue concealing a certain scepticism when it comes to investing in SHM technologies. This is likely imputable due to the lack of clear information about the practical benefits associated with the implementation of systematic monitoring routines and proactive prevention measures. In general, major efforts are needed in terms of synergetic knowledge-transfer to increase public awareness and embed the culture of prevention at all societal levels [24].

The main scope of this chapter is to introduce the subject of structural health monitoring to a broader audience, including researchers and practitioners engaged in heritage conservation programs, but also non-expert readers. To this end, the work is organised in two main sections: the first one focuses on the operational workflow of the SHM process, describing all the different stages of the procedure and providing practical recommendations for its successful execution, whereas the second section presents a real case-study application. The structure under analysis is the Collegiata of Santa Maria in Visso (Italy), a cultural heritage building severely damaged by the seismic sequence that hit Central Italy in 2016–2017. This case study is selected to demonstrate the added valued that SHM-based information can bring during the post-earthquake recovery phase of damaged heritage buildings and to serve as an example on how SHM can be exploited to improve cultural heritage preparedness to future earthquakes.

## 2 Fundamentals of Structural Health Monitoring

Structural Health Monitoring (SHM) can be defined as the systematic process of observing, tracking and analysing the in-service behaviour of a structural system using data periodically sampled, either in a continuous or intermittent fashion, in order to assess its health state under the inevitable ageing and damage accumulation resulting from operational and environmental conditions [25]. The process is essentially data-driven and can rely on different sensor technologies to collect data. As historical buildings are characterised by a complex behaviour because of the interaction among different – and often heterogeneous – elements, monitoring the entire structure with sensors becomes economically and technologically not feasible, thus only data strictly necessary to track key parameters useful to define performance standards are acquired.

The SHM workflow is composed of four main stages (Fig. 1): (1) state indicators selection, (2) architecture definition and data acquisition, (3) data processing and feature extraction, (4) data analysis and interpretation.

**Stage 1 – State Indicators Selection.** SHM can involve the measurement of different state indicators, i.e. quantities of various nature whose selection must be made based on their meaningfulness in improving the knowledge of the structure and in describing the phenomenon that needs to be monitored. Preliminary onsite inspection activities are fundamental to drive this stage. Typically, one can distinguish between static and dynamic structural monitoring. In the former case, monitored quantities are quasi-static parameters, such as strains, inclinations, crack widths, whose variation is so slow that yields infinitesimally small changes in the system's behaviour, thus major effects can be

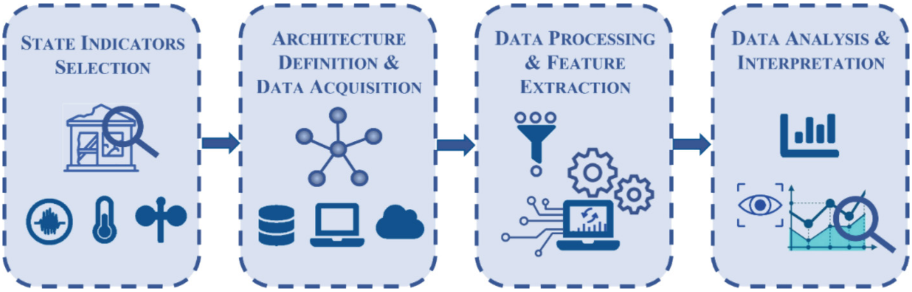



**Fig. 1.** Structural Health Monitoring workflow.

appreciated over long periods of time [8, 19]. Conversely, in the latter case, monitored quantities are dynamic parameters, like natural frequencies, damping ratios and mode shapes, whose variation is associated with the time-dependent vibration response of the structure to an input force and can occur within brief time intervals, sensibly affecting the global system's behaviour in the short period. As dynamic parameters are related to the physical and mechanical properties of the structure, they result very sensitive to damage-induced structural changes [26–31].

Common problems that might need monitoring in heritage structures range from material degradation to foundation settlements, cracking and deformations. As damages originating from different causes can exhibit similar visual characteristics and observed symptoms have not always a univocal relationship with their supposed cause, it is often necessary to track static and dynamic parameters simultaneously in order to be able to explain specific behaviours. In this regard it is worth stressing that measured response quantities can be also strongly influenced by ambient factors, whose seasonal fluctuations may induce displacement and stress variations in the structure, modify the crack distribution within the material and produce non-negligible shifts in the modal properties, ultimately masking irreversible damage-induced changes [19–22]. Due to that, besides structure-related state indicators, it is common practice to track environmental parameters, like temperature and relative humidity, through ambient sensors in order to know their variations and eventually filter out their effects from the structural signatures.

**Stage 2 – Architecture Definition and Data Acquisition.** This stage of the SHM process involves both the selection of the sensor types, which is directly correlated with the type of features to extract, and the definition of the best network topology for a cost-efficient architecture of the SHM system. The response of the structure can be measured by any kind of device (such as accelerometers, displacement/velocity transducers, inclinometers, strain gauges, or fibre optic sensors, to mention a few) able to convert mechanical motion or vibrations into proportional electrical signals, ready to be processed by the data acquisition system (DAQ). For instance, crack meters or displacement transducers can be located across existing cracks to monitor their opening rate over time (Fig. 2a); uni- or bi-axial inclinometers can be employed for measuring the angles of slope of piers, columns and walls with respect to the gravity direction (Fig. 2b); accelerometers can be used to record the vibration or change in motion of the structure at selected points (Fig. 2c); extensometers can be aimed at evaluating strains or stress values in tie-rods (Fig. 2d); and so forth.

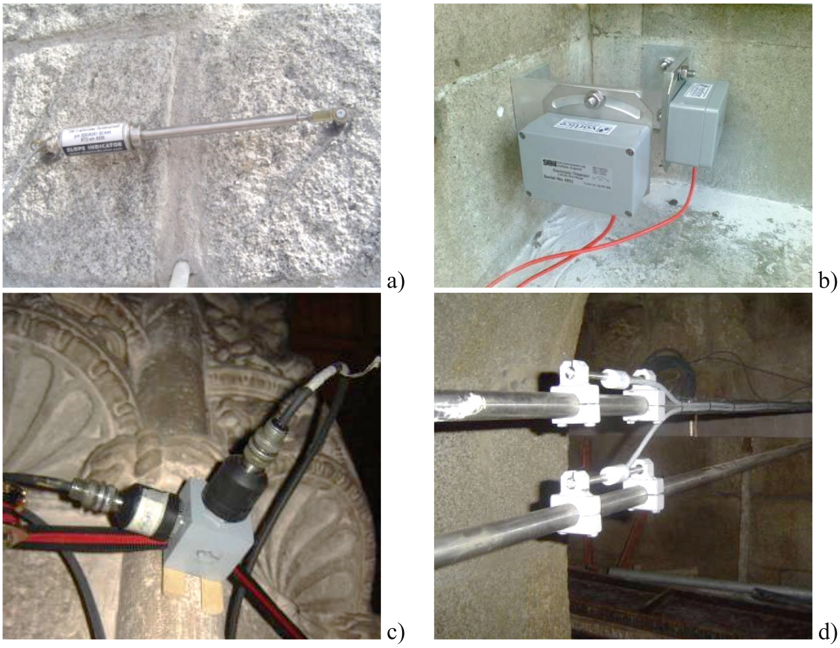



**Fig. 2.** Examples of sensors for SHM: (a) crackmeter; (b) uniaxial tiltmeters; (c) uniaxial piezoelectric accelerometers; (d) extensometers.

For the purposes mentioned above, either traditional tethered sensing systems or modern wireless sensing technologies can be adopted (Fig. 3). The former resort to arrays of sensors deployed at critical spots across the structure and wired back to a single centralised DAQ system where data are stored and processed. The latter rely on distributed autonomous sensing units – not physically linked – provided with onboard software for data collection, self-interrogation, and wireless communication to a central database through IoT gateways [25].

The choice of the SHM architecture and data acquisition system is application-specific and is driven both by technical and economic considerations. Cabled systems are extremely reliable in communication but lack flexibility in terms of architecture and sensor topology as the large number of accompanying wires – besides being susceptible to tearing and noise corruption – does require a significant amount of time and labour for installation and maintenance, making prohibitive the realization of sensor networks with high spatial density [25]. This might be an issue when a greater monitoring fidelity is demanded, for instance in the case of SHM-based damage localization strategies [32]. Modern wireless sensor networks represent flexible and relatively low-cost monitoring platforms that can easily overcome the limitations of tethered systems, being quick to install and highly scalable. Yet, the overall architecture of the system must be well

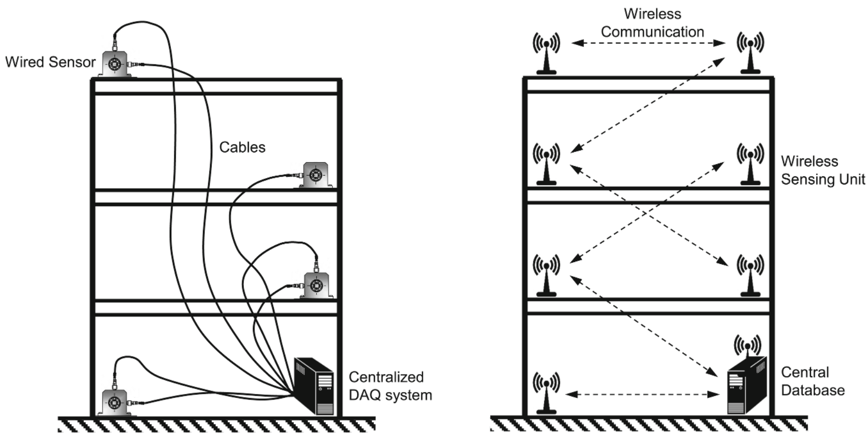



**Fig. 3.** Schematic configurations of current SHM technologies: tethered (left) versus wireless (right) [25].

conceived beforehand because these systems might face telemetry problems related to sensor synchronization, radio interference, long-range data communication and power consumption of batteries [33], risking to compromise the outcome of the SHM process when high sampling rate acquisitions are involved as in the case of vibration-based dynamic monitoring. In this sense, two-tier network topologies with cluster nodes provided with sleep/wake cycles can help improve the functionality of wireless sensing network, reducing energy consumption and avoiding data inundation at the same time [34].

The intervals at which data should be collected is another issue to address at this stage. Indeed, the typological diversity of the features to extract demands not only different sensing devices but also different sampling rates for the data acquisition. Slow-varying static measurements need punctual recordings for which lower sampling rates are sufficient, e.g. one or two samples/hour, whereas time-dependent dynamic measurements need continuous acquisitions with much higher sampling rates, e.g. from 200 up to 1000 datapoints/second, based on the frequency range of interest for the structure. Moreover, in case of ambient vibration recordings, being the input excitation unknown, the time length of the acquisition window should be at least equivalent to 1000–2000 times the fundamental period of the structure in order to ensure sufficient accuracy for the subsequent feature estimation.

**Stage 3 – Data Processing and Feature Extraction.** Acquired raw data come in a variety of forms and need to undergo a preliminary processing stage to facilitate the extraction of meaningful information ready to use for condition assessment. This stage includes different tasks, such as (1) data cleansing for identification and correction/removal of incomplete records and outliers, (2) data detrending for deletion of underlying mean trends and distortions, (3) data filtering for removal of undesired signal components (e.g. moving average filters for static measurements or frequency filters for dynamic recordings), and (4) data decimation or down-sampling for reducing the sampling rate of the recorded signals and speed up the time for the subsequent feature extraction process (Fig. 4). This last task is applied only to highly dense data streams, such as vibration signals in which the Nyquist frequency is much greater than the highest frequency of the signal, hence decimation can help remove the excess bandwidth and reduce both the sampling frequency of the signal and the computational resources required for further processing and storing that signal. Automatic data processing handles data more rapidly than manual data processing and requires considerably less human interaction. Howsoever, to guarantee unbiased estimations, data manipulation must be performed without altering the degree of accuracy and consistency of the original datasets of information. In case of multiple sources, fusion techniques can be employed to integrate data from multisensor environments and achieve improved inferences.

Once processed, data can be exploited to derive case-specific informative features or key performance indicators (KPIs), reduced in dimensionality with respect to the initial sets of data and non-redundant, that can be easily managed for classification purposes and novelty analysis. KPIs can be considered as specific time-dependent quantifiable measurements whose careful examination enables to assess the system's performance against targets, whether these be technical, environmental, or financial [35]. Common programming environments are provided with built-in commands or third-party add-ons to perform the feature extraction task. Because long-term monitoring processes always envision the comparison of many feature sets obtained over an extended period of the lifetime of the structure in operational conditions, it is pivotal resorting to data reduction techniques robust enough to retain feature sensitivity to the structural changes of interest. This is particularly true when dealing with vibration-based dynamic monitoring quantities, for which the volume of original data can be cumbersome and unwieldy to manage. In such cases, time-domain Stochastic Subspace Identification (SSI) methods can be considered among the principal approaches for the automated extraction of synthetic damage-sensitive modal features from output-only data. SSI procedures are based on the state-space representation of a discrete linear time invariant system under unknown excitation and can be implemented in two variants, i.e. covariance driven (SSI-Cov) and data driven (SSI-Data), allowing to track even closely spaced vibration modes which frequency-domain methods often fail to identify. SSI-Data operates directly on measured output response data without processing it. On the other hand, SSI-Cov requires that covariance functions are first estimated from raw output time histories, and it is these covariance functions that SSI-Cov utilizes for the purpose of modal parameter estimation [36, 37].

Regardless of the formulation, SSI algorithms always require the selection of a user-dependent input parameter, i.e. the model order, to process the data and create stability plots (or stabilization diagrams) in order to search for the system's eigenfrequencies as vertical alignments of stable poles over many different model orders (Fig. 5). The maximum model order should be large enough to enable the identification of the fundamental modes of the structures without incurring into the appearance of many spurious or unstable poles. Different values can be tested to find the model order that better fits the experimental data and leads to the best stabilization diagram [8]. For an extensive description of automated modal extraction procedures, interested readers can refer to [36, 38].

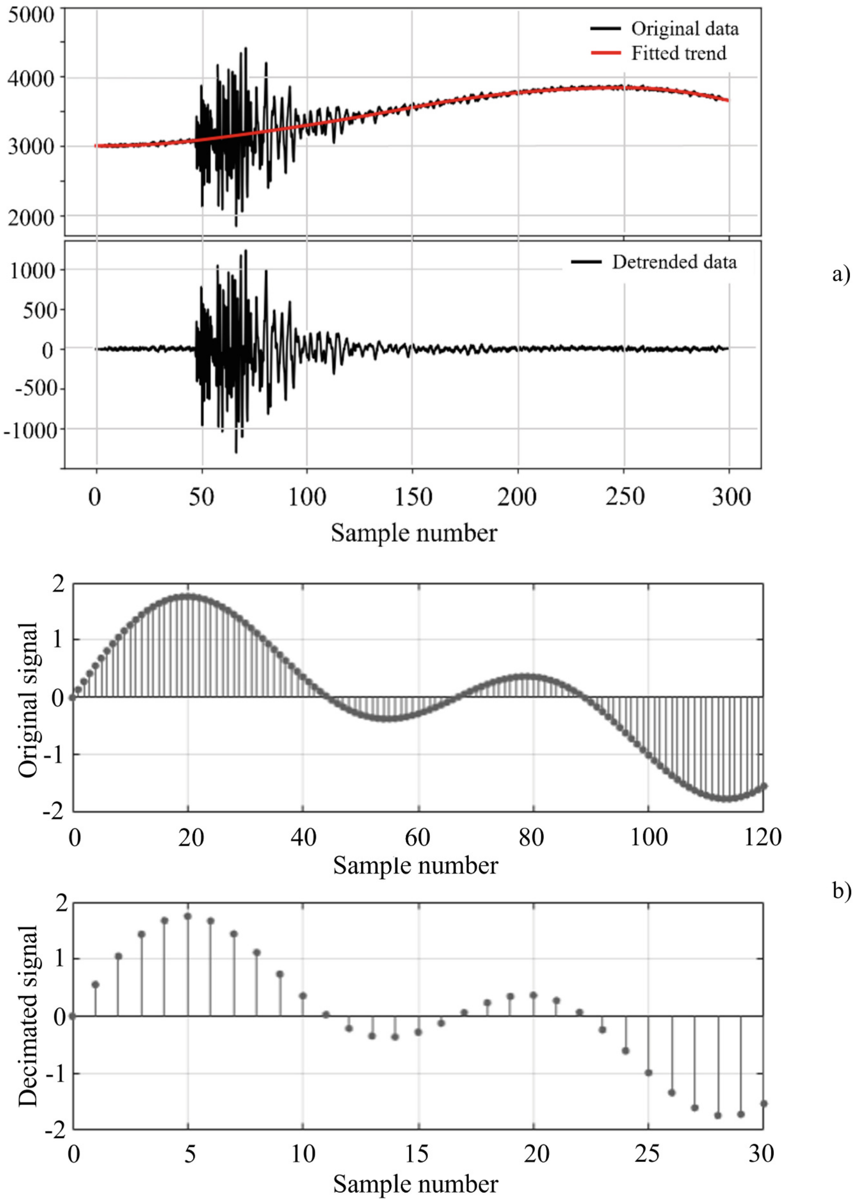



**Fig. 4.** Examples of data processing tasks: (a) detrending and (b) decimation.

**Stage 4 – Data Analysis and Interpretation.** The last stage of the SHM process is devoted to the inspection and modelling of the extracted features with the goal of discovering relevant behaviours, uncovering patterns and trends, and supporting informed decision-making. Diverse tools ranging from simple statistical correlation techniques,

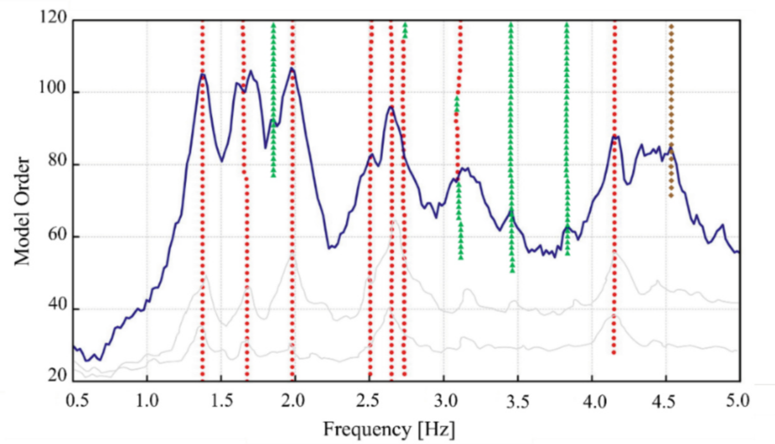



**Fig. 5.** Typical stabilization diagram obtained from the SSI-based feature extraction process: alignments of stable modes in red; unstable modes in green and noise modes in brown.

regression analysis models and control charts to more sophisticated data mining algorithms can be applied in order to measure possible relationships among the monitored parameters, identify deviations from the expected response and discriminate between healthy and anomalous features (Fig. 6a) [12, 21]. Static or dynamic regression models are often used at this stage to filter out components related to reversible seasonal fluctuations from in-field measurements and eventually unmask irreversible damage-induced changes (Fig. 6b) [8, 9, 19, 22].

Scientific data analysis and interpretation can be performed either manually or implementing automated analytics mechanisms that require little or no human interaction. In the last decades, with the progress of artificial intelligence (AI) tools, machine learning algorithms are rapidly taking over in data science applications in order to achieve dynamically enhanced and fully automated intelligent data analyses. Two basic approaches can be distinguished in this regard: supervised learning and unsupervised learning. When labelled datasets are available from an initial reference condition, supervised approaches can be applied to train or supervise algorithms into classifying data or predicting outcomes, whereas in case of unlabelled datasets, unsupervised approaches able to explore data on their own are required. Classifying big data from long-term monitoring campaigns can be a true challenge in supervised learning, but the results are highly accurate and trustworthy. Conversely, unsupervised learning can handle large volumes of high-dimensional data in real time but there is higher risk of inaccurate results as the unsupervised model develops its own understanding and clustering of uncategorized data, without predefined input and output information. As a consequence, unsupervised approaches still need human interaction for validating output variables.

By delivering crucial information on the causes of trends and correlations between variables, SHM insights and data models can improve the diagnosis of heritage buildings to a great extent, playing a fundamental role in evaluating the structural health, selecting the most appropriate retrofitting measures, assessing their effectiveness, and

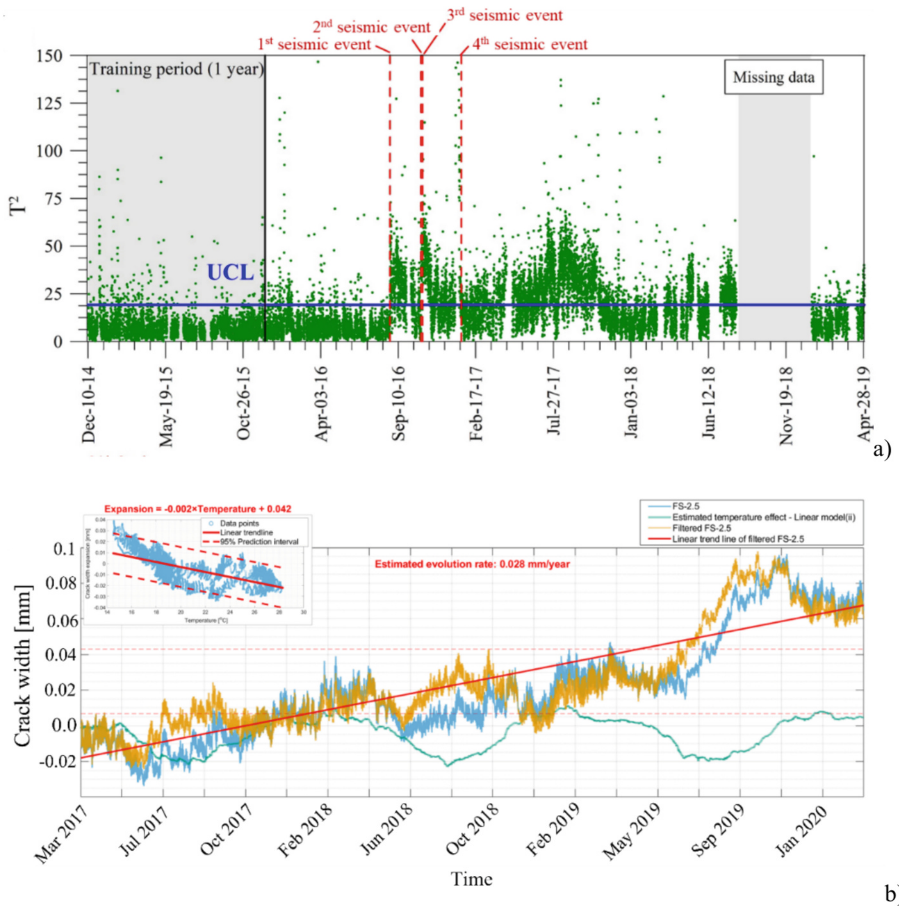



**Fig. 6.** Examples of statistical data analysis techniques: (a) control charts for post-earthquake anomaly detection (adapted from [21]); (b) regression analysis for filtering out temperature effects from crack width evolution (adapted from [19]).

ultimately building predictive models to forecast the future response of the structure against potential scenarios.

## 3 Application to the Collegiata of Visso

In the framework of the OPHERA project (607601-CREA-1–2019-1-IT-CULT-COOP1), in March 2021, an advanced structural health monitoring (SHM) system was installed in the "Collegiata di Santa Maria" in Visso (Macerata province, Marche region, Italy) to assess the structural condition of the religious compound still standing severely damaged from October 2016, when a series of major earthquakes with magnitude Mw ranging between 5.0 and 6.5 (the second seismic sequence, after the first one in August 2016) struck Central Italy causing widespread damage and countless losses. Beyond its remarkable tangible value, the Collegiata represents the physical expression of the intangible layered historical identity of the Visso community and its preservation is a cultural, economic and societal requirement. Hence, the necessity to fully characterize from an experimental point of view the vibration response of the Collegiata so as to drive targeted structural interventions that could bring the church back to its former glory.

After a brief historic background on the Collegiata and a concise description of the earthquake-induced damage exhibited by the structure, the main steps leading to the conceptual design of the SHM system architecture and to the definition of the most appropriate sensor network topology are presented, along with a preliminary insight into selected results that will act as comparative baseline throughout the post-earthquake recovery phase of the Collegiata until completion of the restoration process.

### 3.1 Case Study and Surveyed Seismic Damage

The Collegiata of Santa Maria is considered one of the most emblematic examples of cultural heritage buildings damaged by the seismic sequence that hit Central Italy in 2016. Built in Gothic-Romanesque style, it stands in the main square of Visso (Fig. 7), municipality located about 3 km away from the epicentre of October 26. The original religious space, dating back to 1143, consisted of a small Romanesque parish church and a square belltower. Because of the growing population, this space become soon insufficient to accommodate the faithful, requiring the construction of a larger environment. A single nave space in Gothic forms, i.e. the current church, was therefore erected on the side of the former parish church, incorporating the primitive belltower. Consecrated in 1256 and awarded with the title of Collegiata in 1517, the new church was later enriched with a sacristy, an apse and a round arched splayed portal, flanked by two stone lions, in the side wall facing the square (Fig. 8) [39]. The interior was embellished throughout the centuries with frescos, paintings, altars, and statues of considerable value, including a XVII-century altar with a Romanesque polychrome wooden statue representing the "Madonna Bruna", an impressive fresco depicting St Cristopher carrying baby Jesus unearthed in 1992, a monumental organ with a wooden choir loft and a carved wooden ceiling with paintings, both from the XVIII century (Fig. 7c).

From a geometrical standpoint, the compound stretches over an area of 810 $m^2$ and currently includes four main blocks: (1) the church; (2) the chapel; (3) the belltower and (4) the sacristy. The overall internal dimensions of the single nave church are about 12 m $\times$ 29 m in plan and 14 m in height, while the recessed apse features a polygonal form with an inscribed radius of nearly 4 m. Directly accessible through a masonry arch opening pierced in the lateral wall opposite to the entrance is the chapel with remains from the primitive parish church, a smaller space with a pseudo-rectangular plan of about 7 m $\times$ 14 m divided in two naves by octagonal stone pillars about 5 m high supporting a cross vault ceiling. Next to the arch opening is another door connecting the holy space of the church to both the belltower and the sacristy: the former is characterized by a square plan of 4 m inner side and a height of 40 m with double and triple lancet windows and an octagonal ogival cusp at the top; the latter has a rectangular plan of 13 m $\times$ 5 m and consists of two floors, of which the first one is placed at a height of nearly 2 m from the floor of the church and is covered by barrel and cross vaults.

(a)

(b)

(c)

**Fig. 7.** Collegiata of Visso before the earthquake of 2016–2017: (a) aerial view; (b) exterior view of the church façade (https://viaggimedievali.com/2014/01/31/visso-la-perla-dei-sibillini/); (c) interior view of the main nave.

As the construction of the Collegiata stretched over more centuries, different masonry materials can be distinguished [40]: particularly, apse and entrance façade are made of rubble masonry covered by travertine blocks, the façade opposite to the apse is built in regular limestone stones, and the remaining walls are made of rose stones. The XVIII-century wooden ceiling bridging the space above the church nave is suspended to the roof trusses (originally in timber but later replaced with steel trusses) by a wire hanging system, while the roof above the apse semi-dome is supported by wooden beams lying on a concrete ring-beam running along the perimeter wall.

The 5.9 magnitude earthquake of October 26, 2016 caused serious damage to the historical complex of the Collegiata. During the post-earthquake survey activities, it was

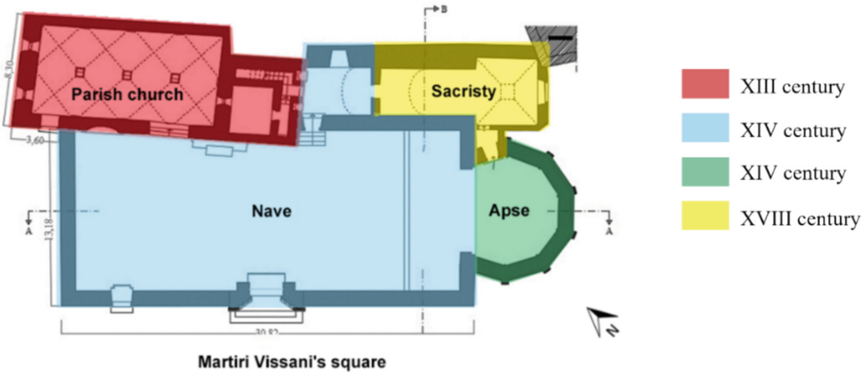


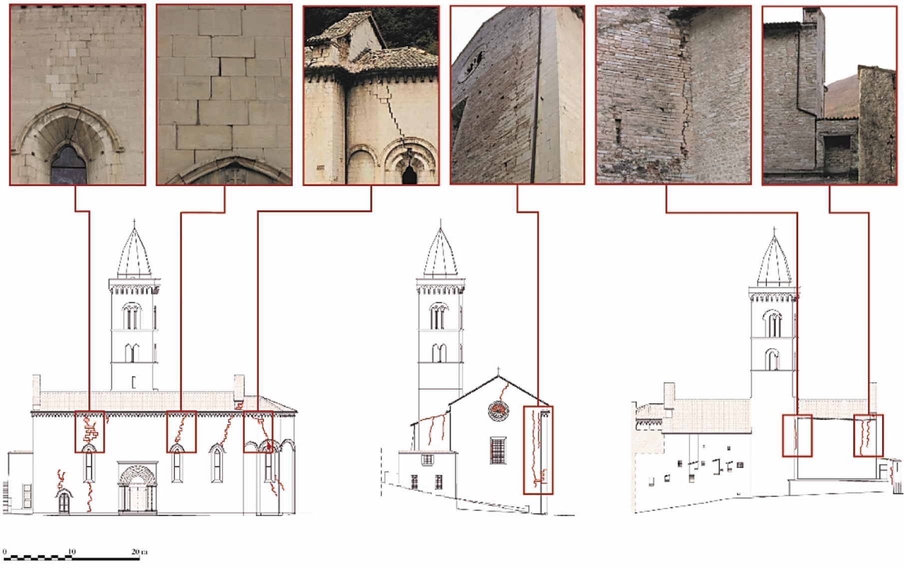

**Fig. 8.** Historical evolution of the Collegiata.

possible to ascertain the onset of out-of-plane overturning mechanisms involving both façade and apse, the concurrent activation of the transversal response of the nave together with in-plane shear mechanisms of the side wall where diagonal cracks developed around the stained-glass windows, as well as the formation of through-passing cracks in correspondence of masonry discontinuities and plan-altimetric irregularities (Fig. 9). The tower suffered extensive damage as well, with the most serious cracks appearing at the intersection with the adjacent chapel wall as a result of the seismic hammering due to the different vibration periods of the two structural units [40]. Evident disconnections also appeared in the vaulted systems of sacristy and apse.

According to the criteria defined by Grünthal [41], an overall damage index $i_d$ equal to 0.54 was estimated, being $i_d$ the ratio between the sum of the grades $d$ given to each of the 28 possible collapse mechanisms defined for masonry churches by the Italian "Guidelines for the evaluation and risk reduction of Cultural Heritage" [42] - with $d$ ranging from 0 (no damage) to 5 (complete failure), and the number $n$ of activated collapse mechanisms multiplied by five. The Collegiata was therefore labelled as temporarily unusable and many ancient artefacts located therein were rescued and moved elsewhere for preservation purposes. Traditional propping and external tying systems with steel cables were adopted as provisional countermeasures (Fig. 10) to elastically connect the macro-elements identified by the earthquake-induced cracks and inhibit the activation of further damage mechanisms, thus avoiding inestimable losses in case of relevant aftershocks. Unlike traditional props, this type of intervention is minimal for the structure, it does not occupy the ground space, it is faster to apply and easy to remove. The provisional measures are still in place and will not be removed until completion of the restoration works.

## 3.2 Description of the Monitoring System

The complexity of the damage exhibited by the structural ensemble of the Collegiata suggested the implementation of an integrated MEMS sensing system, flexible and easily expandable, with IoT-based remote access/control. Rooted in the knowledge acquired



(a) (b) (c)

**Fig. 9.** Damage survey of the Collegiata after the seismic sequence of 2016–2017: (a) South-West façade; (b) North-West façade; (c) North-East side.

**Fig. 10.** Temporary countermeasures adopted in the Collegiata of Visso after the earthquake of 2016–2017.

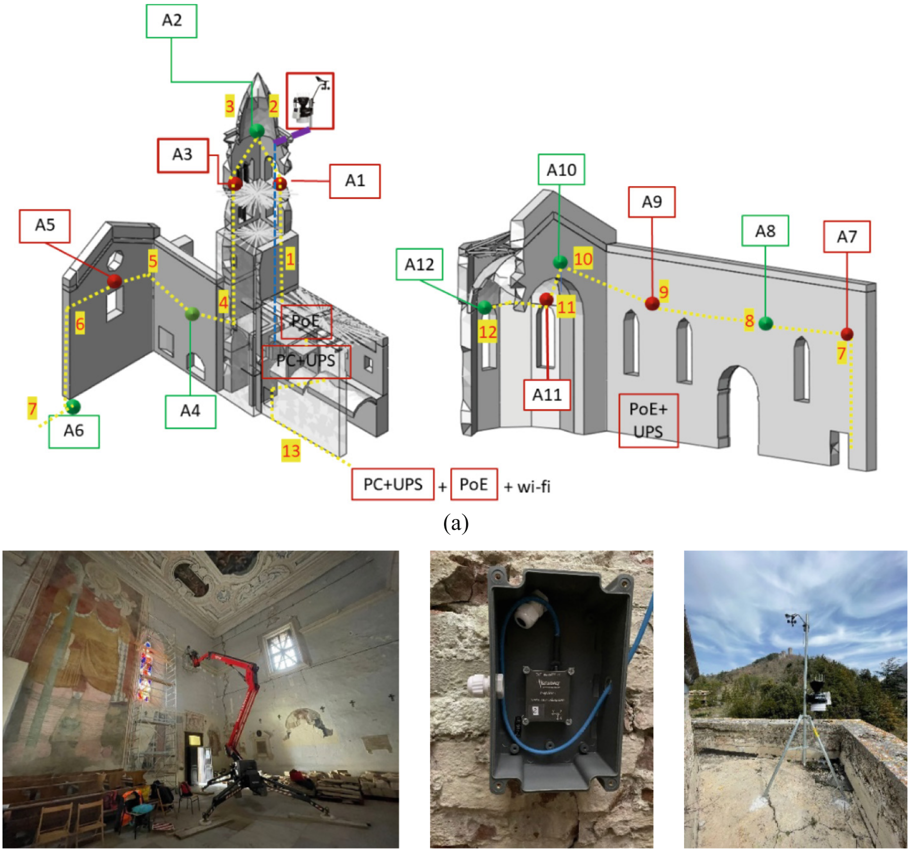
through the post-earthquake reconnaissance activities and preliminary numerical investigations [2, 40], dynamic parameters like natural frequencies, mode shapes and damping ratios, were selected as key indicators to fully characterize the health state of the Collegiata and track its evolution over time, beyond reconstruction, eventually assessing the long-term effectiveness of the consolidation works. The architecture of the entire monitoring system was therefore conceived according to the features to be extracted and in compliance with the indications of the Italian Ministry of Culture Secretariat for the Marche Region, in order to balance the necessary technical requirements with the limitations imposed by the historical value of the construction, trying to attain the maximum quality of SHM information while minimizing the visual impact of both sensors and wiring system inside the building.

Active since March 2021, the dynamic monitoring system consists of 12 triaxial low-noise precision MEMS accelerometers with a dynamic range between +2.0 g and +8.0 g, a frequency bandwidth of 1000 Hz and an operating temperature from – 20 °C to 60 °C [43]. As shown in Fig. 11, nine accelerometers are deployed inside the church, i.e. one at the base of the structure and eight along the perimeter walls where higher modal displacements are expected, and additional three accelerometers are placed inside the belltower at two different levels, thus counting 36 acceleration channels. The nodes (Fig. 11c), protected by adequate IP boxes, are connected through a single network cable following a ring daisy chain topology and keeping a node-to-node distance of maximum 50 m. All sensing devices are provided with an embedded ADC, aiming at eliminating any noise pick up in analog cabling, as well as an internal microprocessor to transmit acceleration samples over EtherCAT protocol directly into a proprietary software running on a PC, thereby allowing to have ready-to-use output data in g or m/s$^2$. Inter-channel time synchronization is ensured by the same protocol. The system is also equipped with a 4G LTE router for high-speed data transfer to a remote workstation and with a 1600W backup battery power supply to avoid data losses in case of power outage.

Considering the notable influence of thermal variations on the modal features of masonry structures, the dynamic monitoring system of the Collegiata is complemented with a weather station on the highest accessible level of the belltower in order to guarantee an optimal position for the evaluation of the environmental parameters of interest, particularly temperature, humidity and wind-related parameters (Fig. 11d). Owing to the typological diversity of the features to extract, environmental data are collected at a rate of two samples per hour, whereas vibration data are recorded with a higher sampling rate, depending on the type of event:

- 200 Hz for programmed events, namely 20-min events scheduled every two hours on a daily basis, each resulting into 240.000 datapoints per channel/direction. Programmed events are necessary to compare the structural response of the Collegiata over time, detect daily and seasonal fluctuations associated with ambient variables and ultimately filter out their effect from the signals;
- 1000 Hz for triggered events, namely 2-min events randomly recorded whenever the amplitude level of the sensor located at the base of the structure exceeds the threshold value of 0.015 m/s$^2$ established for all three directions, resulting into 120.000 datapoints per channel/direction in each acquisition. Triggered events enable to measure the amplification of the structural response in case of earthquakes.

While triggered events are forced by a known input load, programmed events are recorded in the presence of unknown ambient excitation. Hence, the duration of the dynamic recordings for the latter type of events was purposely set to comply with the time length requirements in case of white noise excitation, thereby imposing a data acquisition window around 2000 times the structure's fundamental period which, for the present case, it was found to be associated with the first bending mode of the belltower ($f_1$




(a)

(b) (c) (d)

**Fig. 11.** SHM of the Collegiata: (a) sensor layout; (b) sensor installation in the main nave; (c) close-up of one of the tri-axial accelerometers installed in the tower; (d) weather station.

= 1.55 Hz, $T_1$ = 0.64 s) [40]. After each acquisition, digital raw signals are automatically detrended, filtered and downsampled in order to create a database of files ready for the modal feature extraction process.

### 3.3 Preliminary Results

The SHM system installed in the Collegiata is enabling to track the response of the building on a continuous basis since March 2021. As an example, Fig. 12 illustrates the time histories in acceleration of two representative nodes located at antithetical positions: node A6, placed at the base of the structure, and node A2, located at the highest accessible point of the belltower. Their significant statistics are summarized in Table 1. The magnitude of the vibration level expressed in terms of Root Mean Square (RMS) allows understanding that the level of ambient excitation is extremely low and so is the signal-to-noise ratio, factors that can hamper the feature extraction process because weakly excited modes are not steadily identified. This setback was somehow expected, in fact the Collegiata is located within the area declared as red zone since the aftermath of the 2016 Central Italy earthquake, thus public access is forbidden. Moreover, the monitoring is taking place during the pandemic, hence there is almost no movement even in areas beyond the red zone.

For comparative purposes, Table 2 reports the peak values of the accelerations recorded at the top of the monument (sensor A2) in the three directions during some of the most significant seismic events occurred throughout the monitoring period along with their relative RMS values. In all cases, it is possible to appreciate an increased amplitude level of the vibration response induced by the seismic input. Particularly, the closer the belltower to the epicentre, the higher the amplification.

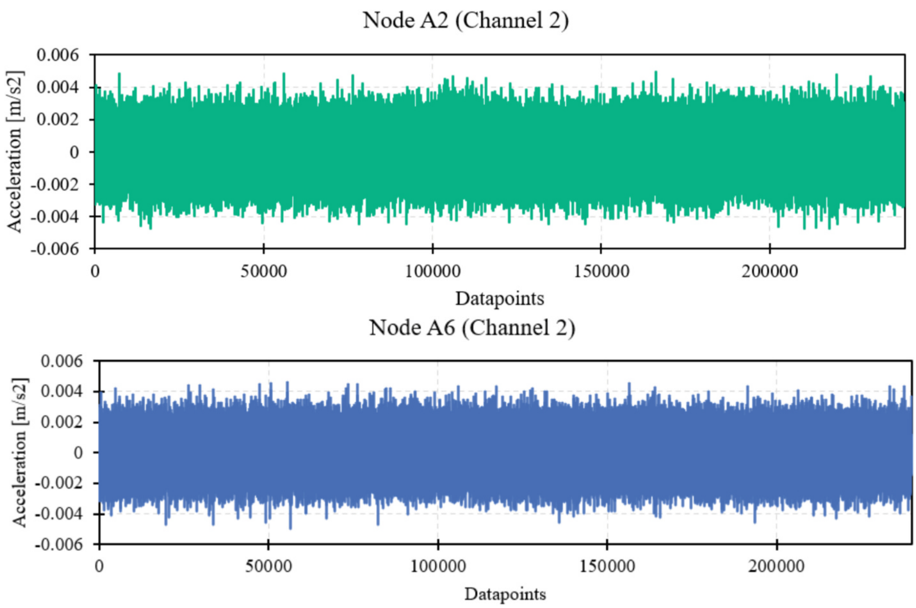



**Fig. 12.** Typical acceleration time histories recorded for nodes A2 (tower) and A6 (base) in longitudinal direction.

Despite the low ambient noise, the relatively dense daisy chain of accelerometers deployed at critical locations across the Collegiata has allowed to identify the main vibration modes of the structure and to obtain a discrete spatial description of their shapes even though local protuberances are evident due to the serious crack pattern of the building, which exhibits clear lines of fracture between the different macro-elements. Table 3 summarizes the results in terms of frequencies, damping ratios and modal complexity factors obtained by processing the 36-channel datasets recorded on 26/04/2021 in the time slot 9:30–9:50 am. The relevant mode shapes are depicted in Fig. 13.

Analysing the outcome of the modal feature extraction process, the following aspects emerge:

**Table 1.** Typical signal statistics for nodes A2 and A6.

| | Accelerations/A2 [m/s$^2$] | | | Accelerations/A6 [m/s$^2$] | | |
|---|---|---|---|---|---|---|
| Direction* | Ch1(vert) | Ch2(long) | Ch3(trans) | Ch1(trans) | Ch2(long) | Ch3(vert) |
| Maximum | 0.0049 | 0.0050 | 0.0080 | 0.0051 | 0.0046 | 0.0076 |
| Minimum | −0.0063 | −0.0048 | −0.0109 | −0.0047 | −0.0050 | −0.0070 |
| RMS | 0.0011 | 0.0011 | 0.0016 | 0.0011 | 0.0011 | 0.0016 |

* Transverse, longitudinal, and vertical directions are defined according to the orientation of the church.

**Table 2.** Comparison of the peak values and RMS (reported between parentheses) of the acceleration response of the belltower in ordinary conditions against those estimated during the most significant seismic events occurred throughout the monitoring period.

| Seismic Event | Date | Magn | Distance [km] | Sensor A2 [m/s$^2$] | | |
|---|---|---|---|---|---|---|
| | | | | Channel 1 | Channel 2 | Channel 3 |
| Ambient vibr | – | – | – | 0.005(0.001) | 0.005(0.001) | 0.008(0.002) |
| Visso (MC) | 21.10.18 | 3.7 | 1 | 0.551(0.029) | 0.510(0.023) | 0.347(0.021) |
| Folignano (AP) | 22.09.22 | 3.5 | 20 | 0.066(0.005) | 0.020(0.003) | 0.022(0.004) |
| Costa March. (PU) | 22.11.20 | 4.2 | 110 | 0.010(0.002) | 0.014(0.003) | 0.017(0.004) |

**Table 3.** Dynamic response of the Collegiata: summary of identified modal features.

| Mode | Frequency [Hz] | Damping [%] | Complexity [%] |
|---|---|---|---|
| 1 | 1.55 | 2.50 | 0.52 |
| 2 | 1.90 | 1.38 | 14.25 |
| 3 | 2.83 | 2.63 | 8.74 |
| 4 | 3.45 | 5.59 | 2.55 |

– The first two modes involve the upper part of belltower, namely the levels above the temporary tying system, and feature a significant coupling between bending and torsion. This behaviour is likely imputable to the asymmetric internal geometry of the tower as well as to its peculiar boundary conditions, being the structure confined on three sides. The characteristic frequency values are relatively close to each other, which is expected for slender structures, and the modal damping ranges between reasonable percentages. On the other side, the close inspection of the mode shape configurations allows discerning that, while the modal deflections of the first mode mainly feature in-phase components, the second mode is characterized by marked

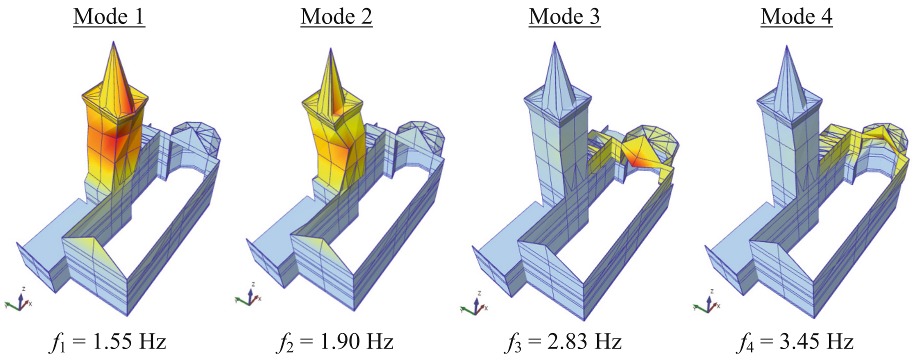



**Fig. 13.** Shape configuration of the first four identified vibration modes of the Collegiata.

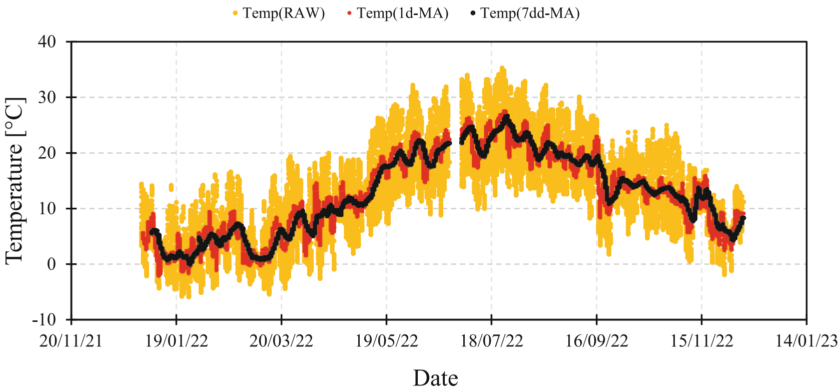
out-of-phase vibrations, displaying clear unsynchronized movements among the different nodes because of the presence of structural damage. Indeed, a higher modal complexity (14.25%) is estimated for mode 2.

– Modes 3 and 4 are predominantly associated with the dynamic response of the apsidal part of the church in longitudinal direction and show synchronized movements involving the polygonal recess, the semi-dome and the triumphal arch. Yet, some local protuberance appears in the areas close to the lines of fracture, especially for mode 3.

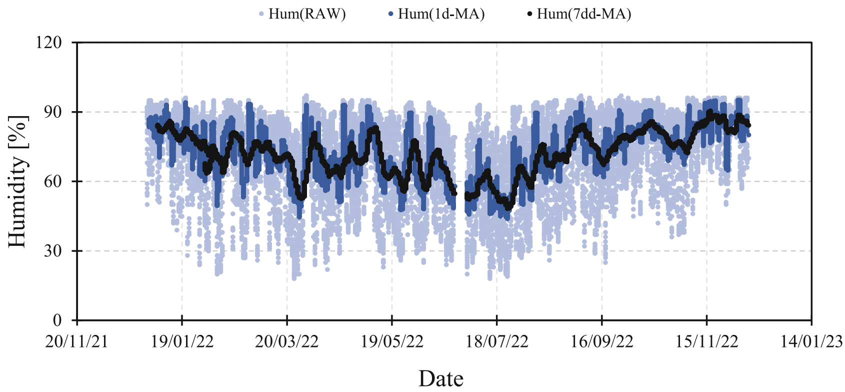
It is worth stressing that the damaged condition of the church did not allow the identification of global vibration modes: indeed, as previously mentioned, the structure does not behave as a whole being split into different macro-blocks which give rise to multiple dynamic local responses. Although compulsory to connect the different parts and prevent further collapse mechanisms, the provisional countermeasures are not meant to reinstate the original stiffness and behaviour of the building, for which ad hoc consolidation works are being planned.

With the aim of supporting the unbiased SHM-based assessment of the Collegiata, environmental fluctuations are kept under control by means of the weather station located at the top of the belltower and active on a regular basis since December 2021. As an example, Fig. 14 presents the yearly trends of the outdoor temperature and humidity measured by the device. Raw data are shown together with their daily and weekly moving averages. A non-negligible seasonal temperature variation can be noted, reading extreme values of −5.9 °C on 26 January 2022 at 5:30 am (winter season) and of 35.3 °C on 24 July 2022 at 12:00 pm (summer season). As for the outside humidity, the range of variation is between 18% and 97%. The statistics of the main ambient parameters, including wind velocity, are summarised in Table 4 for completeness.

To understand the impact of temperature variations on the dynamic features of the damaged structure and quantify possible temperature-induced shifts, Fig. 15 compares the characteristic frequency value of the belltower's fundamental vibration mode estimated from events programmed at seasonal intervals since the installation of the SHM system. The plot enables to notice that frequencies oscillate around the same value throughout the monitoring period regardless of the season, meaning that the structural




a)




b)

**Fig. 14.** Variation of environmental parameters from 30/12/2021 to 09/12/2022: (a) outdoor temperature and (b) outdoor humidity.

**Table 4.** Main statics of the ambient variables monitored from 30/12/2021 to 09/12/2022.

| Results | Temperature [°C] | Humidity [%] | Wind speed [m/s] |
|---|---|---|---|
| Average | 12.2 | 72.6 | 1.6 |
| Median | 12.1 | 78 | 0.9 |
| Maximum | 35.3 | 97 | 27.4 |
| Minimum | -5.9 | 18 | 0.0 |
| St.dev | 8.6 | 18.4 | 2.3 |
| CV [%] | 69.9 | 25.3 | 142.3 |

behaviour is steady, no stiffness variation has occurred following the recent seismic events, and the environmental fluctuations are not likely to influence the belltower's dynamic response.

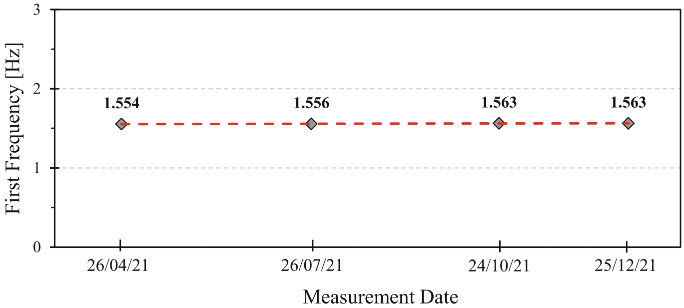



**Fig. 15.** Frequency values of the first vibration mode estimated at seasonal intervals (the trend line is displayed in red).

## 4 Final Remarks

The preliminary results obtained from the analysis and interpretation of the SHM data collected so far have provided a first insight into the post-earthquake behaviour of the Collegiata of Visso. First, the relevant statistics of the typical output response processes at selected points have been estimated to perceive the strength of the recorded random signals; the maximum amplitude level of the vibration response achieved during a few recently occurred seismic events has been computed as well and compared against the one featured in ordinary conditions. In fact, the designed SHM system enables collecting the acceleration time series associated with both programmed and triggered events, such as strong winds and earthquakes. In this regard, it was noted that the response of the Collegiata's belltower remarkably amplifies for higher earthquake magnitudes, and the proximity to the epicentre further accentuates this phenomenon for comparable magnitude values of the seismic input. Yet, no damage-induced frequency variation was detected following these events.

Afterwards, informative modal parameters have been extracted from the processed signals through a semi-automated procedure combining frequency- and time-domain operational modal analysis techniques. It was found that the dynamic response of the building in the low frequency range is primarily characterized by local vibration modes, whose configuration reflects the actual damaged condition of the church and the complex interaction among the different macro-elements defined by the earthquake-induced lines of fracture. Indeed, the provisional props and tying systems put into place in the aftermath of the seismic sequence of 2016 have the sole function to prevent the activation of collapse mechanisms but they are not meant to restore the original stiffness of the building. To this end, case-specific consolidation measures will be undertaken in the upcoming months. It is also stressed that because of the low level of ambient excitation, only the first four vibration modes of the Collegiata could be estimated with their relevant frequencies, damping ratios and shapes. Sophisticated identification techniques will be necessary to process the full set of big data that is being acquired in order to track also weakly excited and higher frequency modes. The continuous monitoring will be performed until completion of the restoration works to closely follow the evolution of the structural response, to keep under control unexpected behaviours, to quantify possible amplification phenomena and to better discern the influence of environmental effects in the long period. The baseline data obtained before the intervention will be used as comparative information to evaluate the enhanced response of the strengthened structure and redefine confidence performance levels.

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# Understanding and Managing Risk in Historic Areas: A Multi-hazard Vulnerability Assessment of the Historic City Centre of Guimarães, Portugal

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**Abstract.** A comprehensive understanding of the elements at risk by identifying the main threats and the exposure of the assets is an essential step towards defining and adopting more effective and cost-efficient risk reduction strategies. Historic urban centres need particular attention due to their irreplaceable cultural value and often high vulnerability to natural and human-made hazards. In the framework of risk analysis and management, this paper presents two index-based methodologies specifically tailored to assess the vulnerability of historic areas to flood and fire hazards through the evaluation of a set of exposure and sensitivity indicators. From the application of the mentioned methodologies in selected areas of the Historic Centre of Guimarães, the present research focuses on the analysis of data collected on-site with different purposes and in distinct periods to perform a multi-hazard vulnerability assessment. Aimed at aiding data management and enhancing the readability and analysis of the results, all the outputs generated for this analysis are mapped using a Geographic Information System (GIS) tool.

**Keywords:** Urban cultural heritage · Historic centres · Index-based methodologies · Vulnerability assessment

## 1 Introduction

Disasters have been more frequent and intense in the last years, causing human, cultural and economic losses. In cities, due to the continuous and accelerated urbanisation, the assessment of risk is necessary and a challenge that involves the whole society. Earthquakes, fires or floods are inevitable hazards that can generate large-scale social, cultural and economic impacts and long-lasting disruption of the urban systems [1].


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Historic centres need particular attention, not only because of the high and irreplaceable cultural value of these areas, as a result of their historical importance, economic role and social symbolism, but also taking into account their high vulnerability to natural and anthropogenic hazards due to the intrinsic characteristics of their buildings. In this framework, index-based vulnerability assessment methodologies assume themselves as valuable and valid tools when many exposed assets require a standardised and straightforward evaluation procedure. Moreover, the combined use of such tools with Geographic Information Systems (GIS) allows for a comprehensive view of the study area and a spatial understanding of the physical and social vulnerability factors involved.

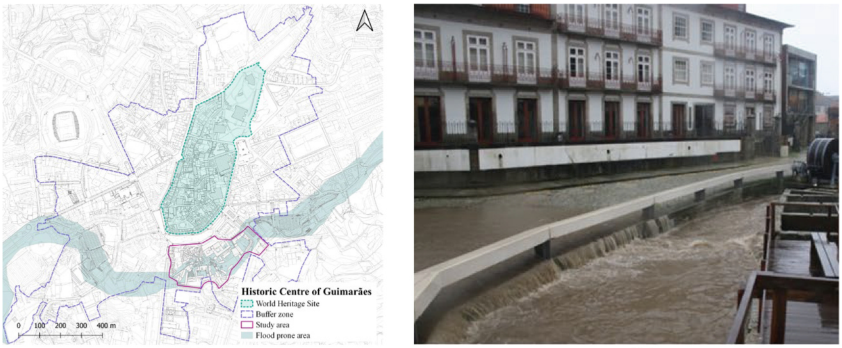
According to the literature review [2], current studies on risk assessment of historic urban areas focus mainly on their physical vulnerability to a single hazard. Despite significant advances in the fields of multi-hazard vulnerability and risk analysis, most of the current methodologies are still unable to integrate the interrelationships comprehensively and effectively between multiple hazards. The first consequence of this is the inability of these methodologies to accurately estimate and prevent the effects of such multiple hazards. Furthermore, a significant part of the multi-hazard vulnerability and risk assessment approaches available in the literature are particularly inadequate to address the specificities and particularities of urban areas and historic buildings.

Considering that any risk assessment is only effective when all relevant potential hazards in the area to be analysed are taken into account [3], this study shows the application of two different index-based vulnerability approaches to assess the level of fire risk and flood vulnerability of a pilot area in the Historic Centre of Guimarães, Portugal. Thanks to their parametric structure, both approaches can be used to outline guidelines to facilitate urban intervention actions and the implementation of appropriate risk mitigation strategies.

## 2 The Historic Centre of Guimarães

The city of Guimarães, known as the cradle of Portugal, is located in the northern district of Braga and has a population of 156,830 inhabitants [4]. As a city of medieval origin, it began to develop approximately between the years 959 and 968. The building typology of the historical centre is based on traditional materials such as granite stone masonry walls, usually found at the ground stories, wood roof structures and traditional clay tiles, along with traditional techniques to build the upper floors as "*taipa de rodizio*" and "*taipa de Fasquio*" used between the 16th century and second half of the 18th century, and the introduction of "*pombalina*" as a structural system around the 19th century [5]. Due to the integrity of its medieval urban layout, the historical centre of Guimarães was classified as a World Cultural Heritage by UNESCO in 2001, recognising two main zones: the intramural zone, with a territorial area of 19,45 ha, and the Buffer zone, which occupies 99,23 hectares of the city's territory [6], see Fig. 1a. Additionally, as an important part of the buffer zone, the Couros zone located on the lower part of the town near the Couros River, was documented by [6] as an urban area intrinsically linked to the dawn of Portugal's nationhood due to the leather industry developed in the 10th century and its impact on the existing urban landscape.

These zones share similar building typologies and characteristics related to their irregular urban morphology and old construction materials, which, added to the increasingly urban and industrial occupation in the historic city of Guimarães, have led to a significant rise in the exposure to anthropogenic and natural hazards, namely to fire and floods. In fact, during the last decades, the severity of flood events increased substantially, leading the authorities to study vulnerable areas in the framework of the Campurbis project developed in 2007, where the Couros zone was geographically identified and mapped as a flood-prone area [7], see Fig. 1b. Besides, the historic centre of the city, due to its nature as an old urban centre, presents all the conditions for a potentially high risk of fire. Between 2006 and 2017, some ten fires were triggered in the historic centre, especially in the buffer zone [8], highlighting the need for assessing the vulnerability of the buildings to these hazards and defining more efficient protection strategies in this area. The present study selected the Couros zone (Fig. 1a) as the pilot area for applying a multi-vulnerability assessment for fire and flood hazards.




(a) (b)

**Fig. 1.** (a) Division of the Historical Centre and flood-prone area; (b) Example of floods in the Couros' basin between 2004 and 2007 (Source: Guimarães City Council).

## 3 Methodological Framework

The present section introduces the fundamentals of the two vulnerability assessment methods applied in this analysis. The approach adopted to characterise the buildings evaluated in this work is also briefly presented and discussed in the following.

### 3.1 Fire Risk Index Method

The simplified fire risk assessment method used in this work was proposed by [9] from a simplification of the A.R.I.C.A. method [10]. The Fire Risk Index Method (FRI) arose as an alternative to conducting a large-scale fire risk analysis, accelerating the information gathering process and optimising the risk evaluation through a large-scale reworked and redefined assessment tool. As discussed in detail by [11], the fire risk index method is composed of two global factors (FGR and FGE), which break down into four sub-factors related to the four phases of a structural fire, i.e., fire ignition, propagation, evacuation and combat (Fig. 2).

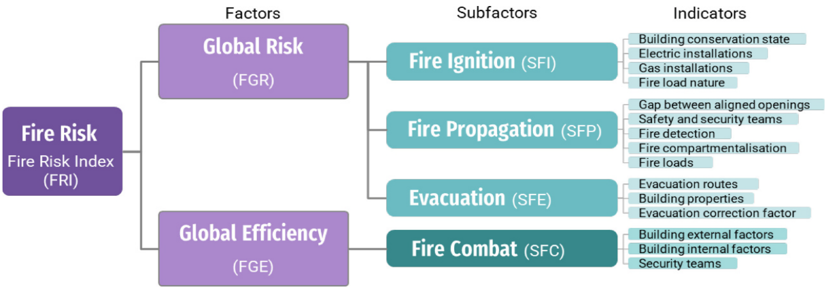



**Fig. 2.** Framework of the Fire Risk Index method.

As presented in Eq. (1), the building fire risk, $FR_I$, is obtained by the quotient between the weighted average of the four subfactors ($SF_I$, $SF_P$, $SF_E$ and $SF_C$) and a reference risk factor ($FR_R$), which depends on the type of building use (Table 1).

$$FR_I = \frac{(1.20 \times SF_I + 1.10 \times SF_P + SF_E + SF_C)/4.0}{FR_R} \quad (1)$$

Sub-factors SFI and SFP are affected by two aggravating coefficients equal to 1.20 and 1.10, respectively. The adoption of these two coefficients is justified by [9] under the premise that interventions in old city centres should be targeted to reduce both the likelihood of fire occurrence and propagation.

**Table 1.** Reference risk factor, $FR_R$, for different types of building use.

| Reference risk factor | Building use | |
|---|---|---|
| | Residential | Service or industrial spaces, libraries and archives |
| $FR_R$ | $0.19 + 0.25 \times F_c$ * | $0.10 + 0.25 \times F_c$ * |

* $F_C$ is a correction factor that can assume the values of 1.10, 1.20 or 1.30, for a building of $< 3$, $< 7$, and 7 + floors, respectively

It is worth mentioning that this method has already been applied to assess fire risk in several city centres across Europe, namely in the Historic Centres of Seixal [9] and Aveiro [12], and Latin America, where the authors [13] propose the simplification of the method to make it suitable to be used for evaluating larger historic areas. The Historic Centre of Quito, in Ecuador, is used to demonstrate the suitability of this modified version of the Fire Risk Index Method.

### 3.2 Flood Vulnerability Index Method

As a consequence of the difficulties in quantifying the exposure and vulnerability for flood risk assessment, qualitative methods have been proposed by different authors [7, 14–18]. Those methods categorise and rank assets in terms of exposure and vulnerability. The simplified flood vulnerability method applied in this study was proposed by [7] to assess vulnerability in historic urban areas. According to this method, flood vulnerability was evaluated by two fundamental factors: exposure and sensitivity (Fig. 3), which are composed of a set of indicators evaluated through four classes of growing vulnerability: A (10), B (40), C (70), and D (100). The higher the vulnerability class, the higher the vulnerability of the building concerning that aspect or feature. The Flood Vulnerability Index (FV) is described by Eq. (2).

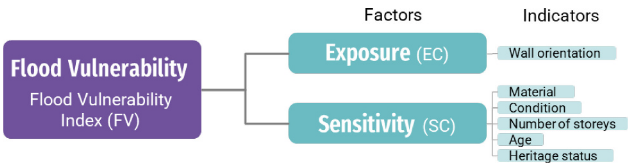



**Fig. 3.** Framework of the Flood Vulnerability Index method.

$$FV = EC \times SC \tag{2}$$

where the Exposure Components (EC) and the Sensitivity Components (SC) product is the Flood Vulnerability Index (FV). The exposure and the sensitivity components were defined in this work based on similar indicators already available in the literature, developed for assessing similar building typologies and structural characteristics under equivalent assessment conditions. Refer to [7] for further details on assessment attributes.

### 3.3 Study Area, Inspection Procedure and Database

The collection, proper inspection, and analysis of the areas studied to test both simplified methods (fire and flood) in the Historic Centre of Guimaraes were published in 2018 for the fire risk method [8, 11] and in 2019, for the flood vulnerability method [7]. The fire risk assessment methodology was applied to 436 historic buildings located within the UNESCO area, whereas the flood vulnerability assessment methodology was applied to the flood-prone zone of the historic centre, which encompasses an area of 7.6 ha located in the buffer zone of the UNESCO-protected area (see Fig. 1a).

Considering that this work aims to perform a multi-hazard vulnerability analysis, the outputs obtained from applying the two methodologies described above are used here to conduct a combined vulnerability analysis where fire and flood vulnerability are analysed together. However, since the previous fire and flood risk analysis were applied to different areas of the Historic Centre of Guimaraes (to the UNESCO-protected area and its buffer zone, respective), it was necessary to apply the FRI method to the buildings located in the buffer zone, obtaining this way an evaluation area that is likely to be affected by either or both hazards (which would not apply to the UNESCO protected area since it is very unlikely it can be affected by floods). The study area adopted in this analysis is thus the one depicted in Fig. 4. As can be seen in the figure, most of the building in this area has a commercial or residential type of use. However, a significant number of buildings are also used for education, hotel business and services.

The information on flood vulnerability from the [7] study was taken directly for the analysis. In contrast, information regarding fire risk has been transferred from the original study area to the flood-prone area, selected as a case study. The criteria used to transfer the information from one area to another are explained in Sect. 4.3. For easy visualisation and analysis of the data, the results of both methodologies were processed through a database connected to a geographic information system. The GIS application software (QGIS 3.16 Hannover) represents each building by its footprint to plot the assessment results.

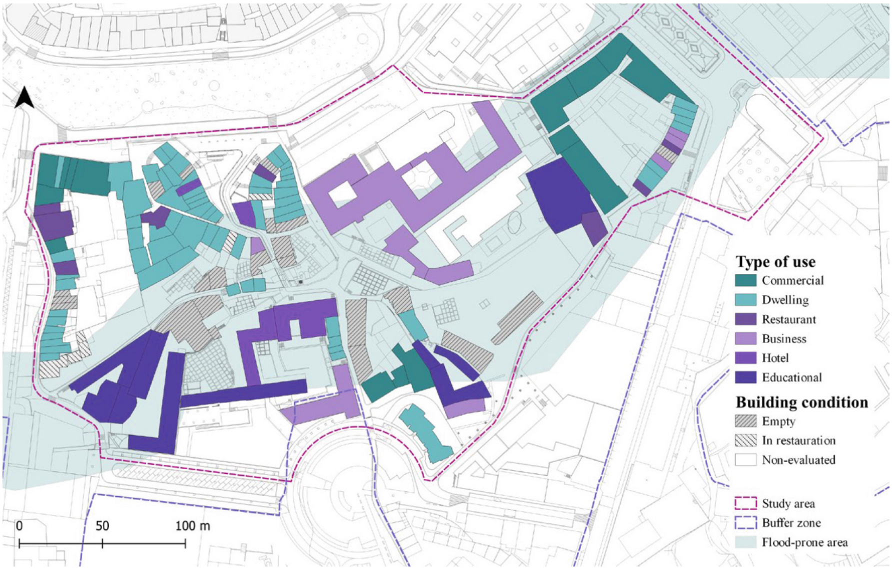


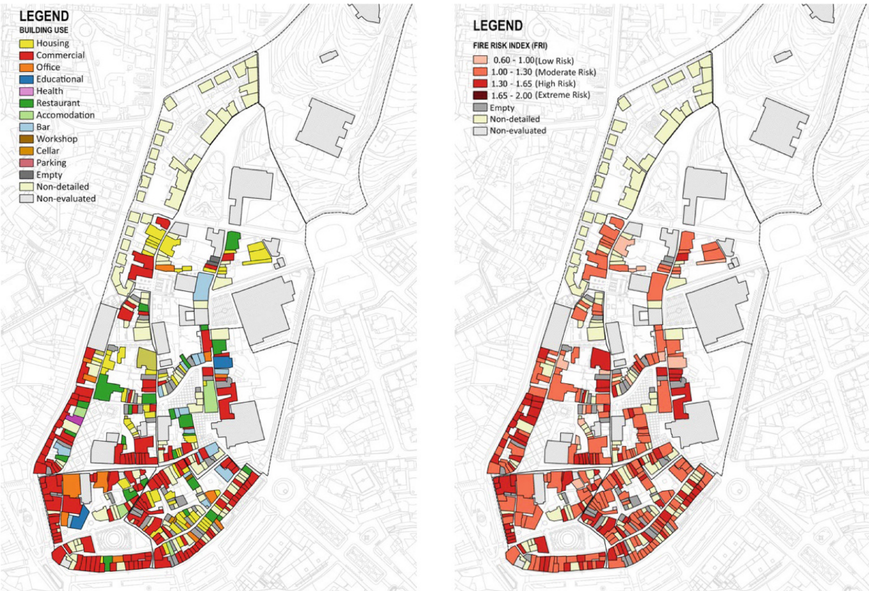

**Fig. 4.** Study area with the identification of the buildings' types of use.

# 4 Multi-hazard Vulnerability Assessment

## 4.1 Fire Vulnerability and Risk Analysis

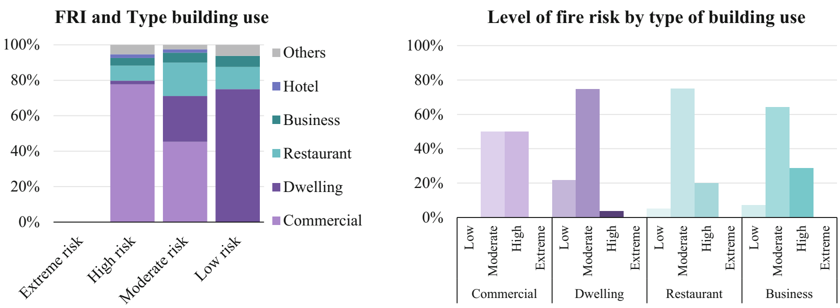
With regard to the fire risk assessment, 436 buildings were evaluated. A significant part of these buildings currently presents commercial use (Fig. 5a), which is one of the most prevalent types of use across the study area, as mentioned before. The overall results are shown in Fig. 5b, where the Fire Risk Index value associated with each building is mapped together with the distribution of the empty buildings.

From the analysis of the results (Fig. 6a), it was possible to observe that the buildings classified with high to extreme fire risks correspond mainly to commercial buildings (78%) and restaurants (9%) which had not renewed the electrical system, did not have a fire detection, warning or alarm system, even though local regulations required it, did not have a safety officer in charge of how to proceed in case of emergency and had a significant amount of materials inside with relevant fire load (i.e. shoes, drugstores, archives, fabrics, etc.). In some cases, there are not enough fire extinguishers to fight fires inside the building.




**(a)** **(b)**

**Fig. 5.** (a) Types of building use identified in the Historical Centre of Guimarães; (b) Fire Risk Index (FRI) results [11].




**(a)** **(b)**

**Fig. 6.** (a) FRI and Type of building use; (b) Distribution of type of use building per FRI.

Buildings with a moderate fire risk are also mainly commercial buildings (45%). In this case, these buildings present low ignition risk, even though deficiencies in detection and alarm systems were identified. Residential buildings arise as the second most risky group of buildings after commercial ones, as can be seen in Fig. 6b. Most of these buildings present semi-refurbished or non-refurbished (i.e., original, often old and inadequate) electrical installations and gas cylinder installations inside the buildings, which can be a potential threat in this kind of buildings—none of the residential buildings evaluated in this work present detection and alarm devices. Fire extinguishers were not identified either. It is worth noticing that the lack of these elements (fire detection, alarm and extinguishing devices) was not considered in this analysis as a risk-increasing factor since the Portuguese fire regulation does not require such devices in residential buildings.

### 4.2 Flood Vulnerability Analysis

From the application of the flood vulnerability assessment approach to the 116 buildings located within the study area, it was possible to observe that, although there is a scatter distribution of the levels of exposure and sensitivity across the study area, some of the buildings with higher levels of exposure and sensitivity are in the south part of the site, precisely within the area that is more prone to flooding. As for the overall distribution of the Flood Vulnerability Index, depicted in Fig. 7, although there is a general dispersion of the vulnerability values over the study area, 10 out of the 14 most vulnerable buildings are located along the identified flood-prone area.

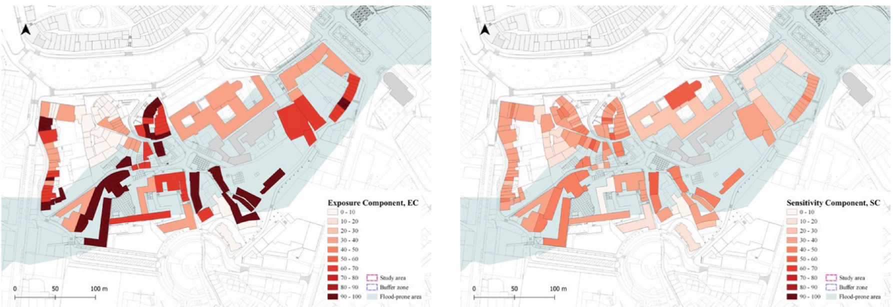



**Fig. 7.** Mapping of Flood exposure and sensitivity indices.

### 4.3 Multi-hazard Vulnerability Analysis

With the information gathered from the application of the fire and flood methodologies, the results must be crossed in a selected study area for the analysis at multi-hazard analysis. For this purpose, the site used for the flood vulnerability assessment was chosen, and, in consequence, the flood vulnerability and risk results presented in [7] can be directly reused in the present analysis. On the other hand, as mentioned earlier, fire risk-related data needed to be transferred from the area displayed in Fig. 5 to the study area adopted for the present multi-hazard vulnerability application.

As can be seen in Eq. (1), the FRI formulation includes aggravating coefficients to the sub-factors concerned with fire ignition and propagation. As discussed above in Subsect. 4.1, the fire risk levels could be related to the type of building use directly, as the different factors will be affected by regulatory restrictions or, in some particular cases, by increased fire load or other use-related aspects. Taking this assumption into account and considering that the buildings in both areas have generically very similar construction and architectural features, the type of use of the building was used in this analysis as a point of intersection between the two areas.

The type of use identified in each of the 116 buildings included in the study area was identified and mapped, and the average FRI value obtained by [11] for that specific type of use was assigned to the building as a starting fire risk value. Table 2 presents the average FRI values used as starting values for this analysis. The percentage of buildings to each one of these average values was assigned is also summarised in Table 2.

**Table 2.** FRI mean per building use in the study area.

| | Class | | | | | | |
|---|---|---|---|---|---|---|---|
| | Commercial | Dwellings | Restaurant | Business | Hotel | Workshop warehouse | Educational |
| FRI mean | 49.30 | 31.63 | 42.53 | 45.04 | 49.04 | 52.97 | 36.75 |
| N buildings | 145 | 57 | 40 | 14 | 5 | 4 | 2 |
| % | 53.7% | 21.1% | 14.8% | 5.2% | 1.9% | 1.5% | 0.7% |

As seen in the table above, around 54% of the buildings were assigned a starting FRI value of 49.30. About 21% of the buildings associated with residential use were assigned an FRI of 31.63. And nearly 15% of the buildings were given an FRI value of 42.53.

## 5 Multi-hazard Vulnerability Mapping – Results and Discussion

Once the Fire Risk Index values are assigned by type of use for each building, they are mapped and combined with the flood vulnerability results through a multi-hazard vulnerability map. For a better interpretation of the data, both indices are overlaid and not aggregated into a single multi-hazard index (Fig. 8).

One of the first observations that can be made from the analysis of Fig. 8 is that 36 out of the 116 buildings evaluated, representing about 31% of the sample, present a fire risk index greater than 40, a value that can be taken as the threshold between moderate and high fire risk – refer to [11] for more details about this aspect. Most buildings that stand out with higher FRI values correspond to commercial and office buildings, restaurants, and hotels.

In contrast, when analysing the flood vulnerability results alone, only 18 buildings (about 16% of the evaluated sample of buildings) present a flood vulnerability index greater than 40, which, similar to the fire risk indicator, is the figure taken as the threshold value between moderate and high flood vulnerability – details about this qualification can be found in [7].

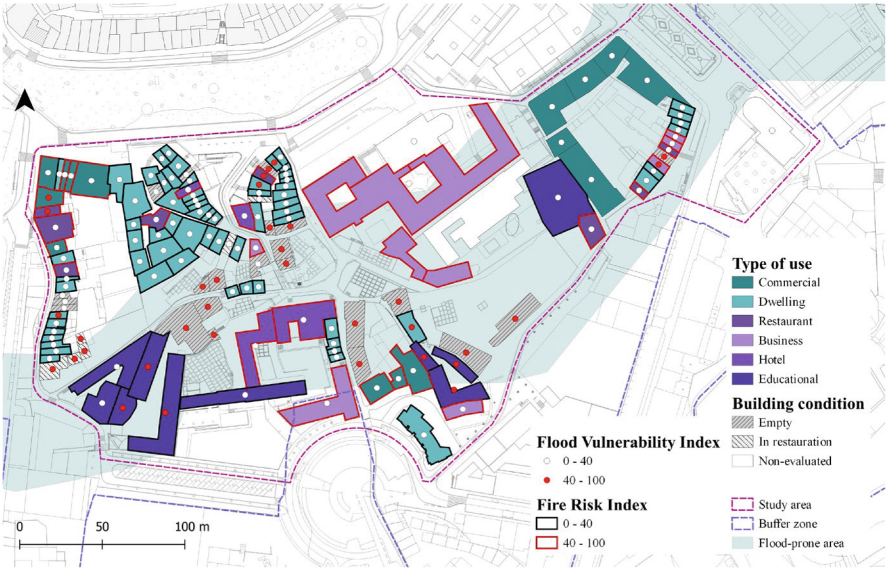



**Fig. 8.** Multi-hazard vulnerability map.

When analysing the fire and flood risk assessment results together, one can observe that only one of the buildings included within the study area presents a high level of fire risk and a high level of vulnerability simultaneously (Fig. 8). As can be seen in Fig. 8, the main reason for this is that probably by chance, most of the buildings presenting higher levels of fire risk are located outside the flood-prone area. Even so, from the combined analysis of the fire and flood results, it is possible to observe that a very significant part of the buildings present a high level of vulnerability or risk to one of the two hazards analysed in this work, which is an important result if the aim is to prioritise vulnerability and risk-mitigation interventions at the urban scale.

Some additional relevant conclusions can be drawn from these results. The first relates to the empty buildings located in the study area. As shown in Fig. 8, most of these empty buildings, which are very vulnerable to flooding events, are found near commercial buildings with high fire risk levels. Although the empty buildings were not assessed for fire risk, poor conservation states can also facilitate the propagation of fire from neighbouring buildings due to the exposure of flammable materials such as roof timbers. On the other hand, the lack of surveillance could delay the firefighting stage. The same applies to buildings under restoration, which always implies the presence of fire-hazardous pieces of equipment. Furthermore, empty or abandoned buildings usually present advanced or accelerated degradation patterns. The presence of cracks and lack of maintenance of the cladding can increase the deterioration of the walls due to excess humidity and the development of non-structural anomalies, which, if not resolved, can easily lead to structural anomalies.

## 6 Final Remarks

This study presented two index-based methodologies for assessing the vulnerability and risk of historic areas to two different hazards. Based on the results obtained from the application of those methodologies in the Historic Centre of Guimaraes, a multi-hazard (flood and fire) vulnerability analysis was conducted. Because the amount of information available to carry out the analysis was heterogenous across the Historic Centre of Guimaraes, it was necessary to adopt a type-of-use-based approach where each building type of use was utilised to assume a starting fire risk index value, which was then modified according to the specificities of each building.

The overlapping of information in the same geographical area, including fire risk and flood vulnerability assessment results, permitted a more in-depth analysis of the vulnerability of the study area, overcoming some of the limitations associated with single-hazard investigations.

Commercial and hotel buildings were found to be the buildings with higher fire risk levels. Considering that the indicators for flood vulnerability evaluation are based on the physical characteristics of the buildings, through this analysis, it was possible to confirm that the occupancy of the buildings is one of the most critical drivers for vulnerability and risk.

The evaluation of the architectonic and construction features of the buildings combined with other criteria like occupancy and type of use allows for a multilevel assessment. The approach presented in this chapter was aimed at giving a first attempt towards such by discussing an approximation to a multi-hazard risk assessment at an individual and group level.

Finally, the analysis of the spatial outputs obtained using GIS allowed us to get a better picture of the spread of exposure, sensitivity and vulnerability results across the study area, which is a fundamental prerequisite to propose more adequate intervention strategies based on actual, local conditions.

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# Digital Guardians: A New Method of Data Management for At-Risk Cultural Heritage in Bavaria

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**Abstract.** 110,000 architectural monuments currently exist in Bavaria. Monument owners, authorities, associations, and other organizations are working to preserve the architectural heritage. Even though this endeavor is mostly successful, some cases are currently at risk. According to estimates around 3,500 of these listed buildings are at risk in Bavaria. This number represents around 3% of the listed buildings. Although the number of endangered objects seems small, each of the endangered buildings is unique and irreplaceable as a contemporary testimony. For this reason, it is essential to know the objects. Therefore, the Bavarian State Office for the Preservation of Monuments and Sites developed a digital database and a data management system based on a GIS to record and manage Bavaria's endangered architectural monuments. An interactive map provides information on the building quickly and easily. An overview of the endangered cultural heritage can be created. In addition to recording the cultural heritage at risk, a database with best practice solutions for sustainable refurbishment is being developed. This database offers a collection of different solutions for different types of buildings (e.g., barns, mills, or castles) that also consider local conditions. The best-practice solutions must be validated and, if possible, monitored after implementation. The object-specific approach of monument preservation is thus transferred to a higher level. The networking of the endangered inventory, therefore, serves to save not only individual buildings but entire groups of buildings.

**Keywords:** Culture Heritage at-risk · data management · geoinformation system (GIS)

## 1 Trash or Treasure?

Trash or treasure? This or similar thoughts go through some people's minds when considering endangered architectural monuments at risk. Some describe the buildings as eyesores, others as jewels in Sleeping Beauty's sleep. So, what kinds of monuments are these? As shown in Fig. 1, around 13% of the endangered monuments on the UNESCO World Heritage List are located in Europe and North America, according to Statista [1].

Bavaria currently has a total of 110,000 architectural monuments. Monument owners, government authorities, associations, and other institutions are working to preserve the


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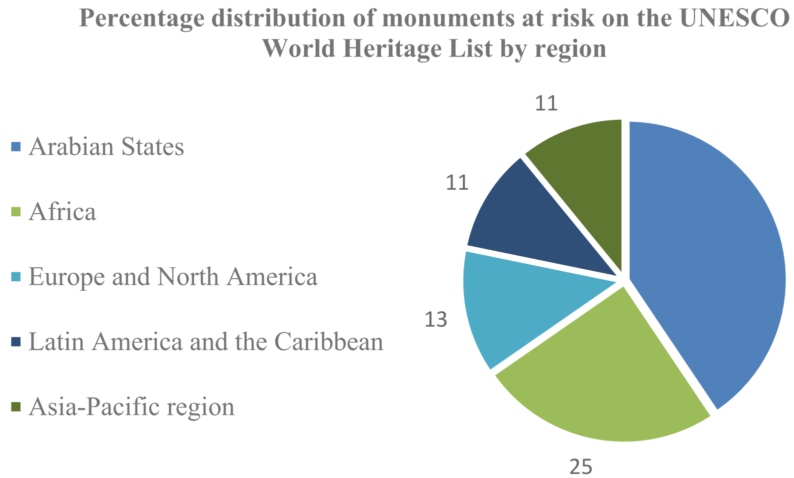


**Fig. 1.** Distribution of listed monuments at risk on the UNESCO World Heritage List by region after [1]

architectural heritage. Although this effort is usually characterized by success, some challenging cases take time to maintain for various reasons. Estimates indicate that there are currently around 3,500 of these individual cases in Bavaria. This number represents just under 3% of the listed buildings. This small percentage may sound like a reasonable loss. Considering that each listed building is unique and irreplaceable as a contemporary witness, not only 3% of the listed buildings would be lost, but 3500 buildings that characterize our cultural landscape and document past times.

The historical buildings show where we come from, and the current way of handling them shows where we are going in the future. Against the backdrop of climate change and the finite nature of resources, we need to consider how we will deal with existing buildings in the future. Disposable culture or repair culture? If the historic buildings at risk have a sustainable existence, helpful insights can also be gained for the non-listed buildings in need of refurbishment. In addition, the renovation of buildings can save grey energy and thus greenhouse gas emissions. As well as best practice examples, it is also possible to evaluate which building structures are more adaptable to changing requirements and climate influences. Therefore, the estimated 3,500 endangered buildings are worth considering for several reasons.

The monuments at risk are currently integrated into the daily routine of monument preservation. They generally require unique solutions and more time. However, resources in monument preservation are limited. The vision is to offer solutions for monuments at risk and to prevent other buildings from being endangered. In addition, the knowledge gained from dealing with buildings at risk expands our understanding of building in existing structures with regard to the challenges posed by climate change.

As Karl Friedrich von Schinkel [2] recognized in 1815, "Only those who know what exists at all can protect it effectively". With regard to cultural heritage at risk, only those who know which endangered monuments exist can take special action to save them. The answer is to develop a digital, systematic overview of cultural heritage in danger, which is still missing. In order to create a systematic overview, the first step is to develop an initial classification system. What is a monument at risk? What information is needed? What is the data used for? Which system enables simple data collection, evaluation, and maintenance?

## 2 State of the Art

Since 1998, there have already been some digital systematic overviews of the built heritage at risk. In addition to listed buildings at risk, some include sites of worship, archaeological sites, parks and gardens, battlefields, wreck sites, and nature reserves [3]. According to Historic England [3], there are two criteria for the risk: the structural condition and the occupancy (or utilization). Occupancy is categorized as ‘empty’, ‘partially occupied’, ‘occupied’, ‘not applicable’, or ‘unknown’. Structures that fall into the category “not applicable” are, for example, walls, gates, gravestones, or boundary stones. The condition is categorized as ‘very poor’, ‘poor’, ‘fair’, or ‘good’. In the case of “good” structural conditions, vacancy only poses a threat. The database from Historic England [3] is updated using status surveys. The register is available as a document or as an interactive map [3]. The primary aim of data collection and communication is to save the architectural heritage at risk. For this purpose, the register is intended, among other things, to draw attention to monuments at risk and inform communities about the condition of their built heritage. The overview should also enable public monetary and time resources to be prioritized for endangered architectural monuments. It is furthermore intended to motivate people to become actively involved in saving endangered architectural monuments. In addition, social and economic research is conducted to understand cultural heritage’s value and identify trends. In parallel to highlighting the risks, the program also communicates successes in saving architectural monuments [3].

Associations or organizations often publish so-called red lists, which register cultural heritage at risk. A transparent system of categorizing when a monument is at risk is often not published. In addition to monuments at risk, some saved and lost monuments are also listed. These digital lists or interactive maps are mostly used to raise awareness and provide information [4–6].

The Deutsche Stiftung Denkmalschutz (German Foundation for Monument Protection) [7] publishes information on listed buildings at risk to collect donations to save the monuments. Again, the criteria for a monument at risk are not specified. Based on the published information, the conclusion is drawn that a monument with severe structural damage, for example, due to natural disasters, is considered to be at risk [7].

Other digital data collections and interactive maps are intended to actively promote the sale of endangered monuments and raise awareness. For example, monument owners can offer their monuments for sale on the Denkmalradar platform of the Leipziger Denkmalstiftung (Leipzig Monument Foundation) [8]. Furthermore, committed individuals can report monuments at risk. Stakeholders involved in the refurbishment of monuments at risk can share their experiences and inspire others with successful projects. In addition to providing information, the platform is intended to help with networking. Volunteers are responsible for registering monuments at risk and publishing successful projects. The accuracy of the data is not verified and is based on trust [8]. The Schweizer

Heimatschutz' [9] red list pursues a similar mission. In addition to raising awareness and motivating volunteers, the platform serves to collect donations.

In addition to isolated digital databases, there are analog collections of endangered monuments, such as information brochures [10]. The International Council on Monuments and Sites (ICOMOS) has published the Heritage at Risk series (World Reports on Monuments and Sites in Danger) since 1999 to inform the general public about the most severe risks to cultural heritage, including UNESCO World Heritage Sites [11].

Overall, it can be concluded that information on listed buildings at risk is usually collected as a digital list or interactive map and occasionally as an analogue list. It is noticeable that, except for the Historic England platform [3], all digital databases are managed by non-governmental institutions. Furthermore, there is often no transparent system for the registration and data management of monuments at risk. Classification as a listed building at risk is often subjective. It is also noticeable that data management is usually outsourced to volunteers, which means that the accuracy of the data is not validated. The register often serves to raise awareness and provide information. Occasionally, donations are collected, or networking between stakeholders is promoted. In addition, successful projects are often published for orientation and inspiration. However, these are usually not evaluated or monitored either.

None of the databases systematically classify the degree of risk. In addition, there is no evaluated collection of best practices for the renovation of groups of buildings at risk to communicate transferable solutions.

## 3 The Way to a Digital Guardian

In order to catalog the cultural buildings at risk, the first step is to define the term "listed building at risk". The definition of the term is based on Heritage England's [3], which has two basic categories: vacancy (or lack of use) and structural damage. However, no different sub-categories of vacancy are defined, but the building is considered vacant as soon as part of the building is vacant. In addition, the damage is only divided into the categories, "damage restricting usability" and "damage restricting stability," which also form their own category. In order to close the research gap identified in the state of the art, risk levels are assigned to the three categories, as shown in Fig. 2. The lowest category (III) is vacancy or lack of use. In this case, the building or a part of the building is vacant but can be brought into use without significant action. The second category consists of buildings that are damaged, which restricts their usability (II). These buildings cannot be used without repairing the damage, such as missing window panes. The top category consists of buildings whose structural stability is not guaranteed (I). They can only be utilized with considerable effort. As shown in Fig. 2, the level of risk and, thus, the actions required for utilization increase from vacancy to limited structural stability. If a building is assigned to a category, it can be assumed that it also fulfills the criteria of the categories below it. For example, it can be considered that a building with damage that restricts its usability is vacant or that a building with damage that limits its stability also has damage that restricts its usability and the building is vacant. Furthermore, it can be assumed that the longer a building stays in one category, the more probable it is to slip into the higher risk level.

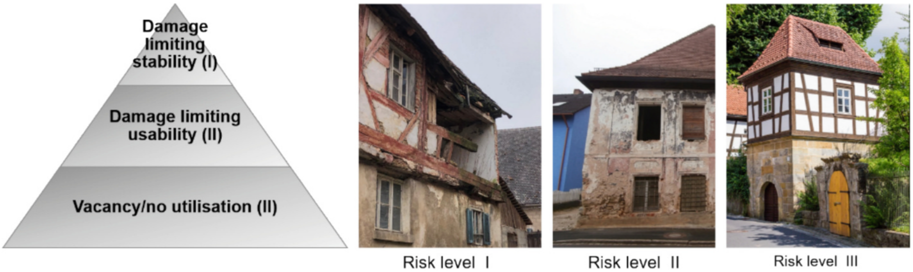


**Fig. 2.** Risk pyramid with examples for monuments at risk [12]

In order to record the necessary data systematically, a thesaurus was developed in the following step. This enables a comparison of the different buildings and a correct statistical data analysis. This thesaurus contains all the relevant information about the monument at risk that is required for a refurbishment and a nationwide comparison. In addition to the location, the monument type, the architectural period and style, the historical and today's function, the construction, the building type, and the risk level are recorded. For example, the function can be residential and the associated building type can be a farmhouse or townhouse. The construction is divided into massive, block, half-timbered, and mixed construction.

In the first step, the data was collected with the help of research in the specialized information system of the Bavarian State Office for the Preservation of Monuments and Sites. The specialized information system (FIS) is a geographical information system. It is used to record all important data on architectural, artistic, and archaeological monuments, as well as movable monuments and listed ensembles in Bavaria. The FIS is used to maintain and update the Bavarian list of monuments and to ensure the participation of the Bavarian State Office for the Preservation of Monuments in monument-related and planning procedures. A list of listed buildings at risk was already compiled there during a re-qualification of Bavaria's monuments between 2009 and 2012. However, this list is not systematized, so the information must be systematized and updated.

Based on this data, the information on the objects was updated, and the objects were systematically recorded. For this purpose, interviews were conducted with stakeholders such as state employees in monument preservation and protection or civic activists. The condition of the buildings was also determined with the help of maps based on satellite data. Employees of the responsible public authority always checked the data.

The data is then collected, analysed, and managed in a Geo-Information system (GIS). The information is collected in a deposited database. An interactive map enables user-friendly access to the information. Depending on the filtering of the stored data, the created nodes are presented in different colours. For example, the common color scheme can quickly identify building types such as barn. The level of risk can be visualized, for example, using a traffic light system (red = highest risk level, green = lowest risk level).

In addition, the update provided initial results on how many of the buildings have been demolished or renovated in the past 12 or 15 years or are still at risk. The traffic light system also offers a clear visualization option here (red = demolished, yellow = still at risk, green = renovated), as shown in Fig. 3.

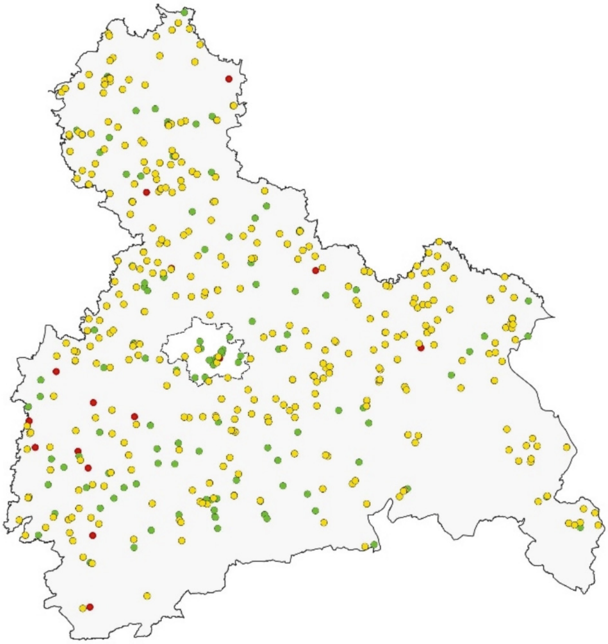

**Fig. 3.** Illustration of demolitions (red), renovations (green), and listed buildings still at risk (yellow) in the district of Upper Bavaria since 2012

The results showed that, on average, more buildings have been renovated than demolished. However, the number of endangered monuments has been increasing since 2012.

Among other things, it is important to know where the listed buildings at risk are located and what types of buildings they are. For Example, data collection has already enabled the identification of groups of listed buildings that are more frequently at risk. In order to systematically address this risk, a best practice catalogue is currently developed for each group of listed buildings at risk. As the monuments in the groups are similar, some solutions can be transferred or at least serve as inspiration. The catalogue is also structured according to a previously defined system. In addition to the initial situation (construction, thermal insulation, use, and lighting), the refurbishment methods are explained, and the final state is described qualitatively and quantitatively. The methods are evaluated to ensure the quality of the refurbishments. Monitoring is to be carried out on a sample basis in the future. The outlook of this paper goes into this in more detail.

## 4 Application Examples of the Digital Guardian

This chapter presents the application of the digital guardian in two case studies.

In case study 1, the aim is to determine how many monuments at risk of a building type are located in a government district. The case presented here shows how many barns in Upper Bavaria are threatened by decay. The ‘Barn’ option can be selected via a drop-down menu to display the barns at risk in Upper Bavaria. Then, as shown in Fig. 4, only the barns at risk in the administrative district of Upper Bavaria are displayed on the interactive map. For this purpose, the addresses and other geodata of the monuments are merged and displayed. By clicking on a marker (colored dot) on the interactive map, the information systematically collected on the endangered monument can be retrieved. The data presented this way enables quick and easy analyses even for non-experts. In addition to the number of barns at risk in Upper Bavaria, it is possible to recognize whether there is an accumulation in a region. It is also possible to see if the analyzed buildings are located in urban or rural areas. By identifying clusters of boundary conditions, transferable solutions can be developed. In addition, it is possible to determine the reasons for a risk and develop countermeasures.

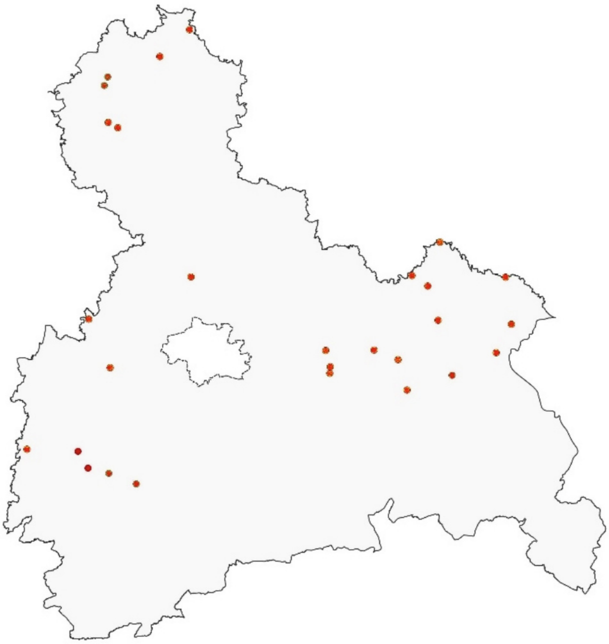

**Fig. 4.** Illustration of the interactive map of listed barns at risk in the administrative district of Upper Bavaria

In addition to collecting data on the barns at risk, the best practice catalog for possible sustainable renovation methods for this type of building is being developed successively. In addition to various utilization options, different methods of thermal energy refurbishment will also be identified. For example, various utilization options are presented that only require structural renovation of the barn but not thermal energy refurbishment. Examples that have already been realized demonstrate the necessary boundary conditions and required action to enable utilization as a roofed marketplace, an art studio used only in summer, or an event hall, to give just a few examples. Various options for thermal energy refurbishment are also shown, depending on the construction and size of the barn, such as complete insulation of the building envelope or a house-in-house solution. The house-in-house solution, shown in Fig. 5, involves placing a smaller building with a high thermal energy standard inside the barn. The barn then only serves as a protective shell against the weather. This solution is often economically and ecologically more sensible and significantly less vulnerable to faults.

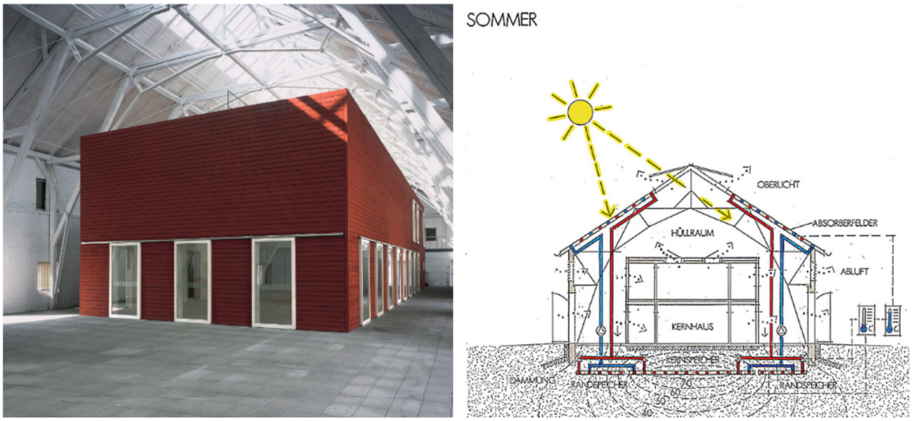


**Fig. 5.** Example of a house-in-house concept, photo (left) energetic scheme (right) [13]

As Case Study 1 demonstrates, a group of listed buildings at risk can be quickly and easily identified. In addition to detailed information, the interactive catalogs already provide an initial overview. Thanks to the data already collected on the boundary conditions, the attached best practice catalog can be used to identify possible solutions that have already proven themselves in practice. The catalog helps find suitable solution for different usage ideas and the planned thermal energy standards.

Case study 2 examines how many monuments at risk are located in rural areas such as hermitages. For this purpose, 'Hermitage' can be selected in the 'Location' drop-down menu to display only listed buildings at risk in isolated locations. In addition to the hermitage selection, the menu distinguishes villages, small towns and large cities. This allows the calculation of the percentage distribution of monuments at risk in terms of location. In addition to identifying the location as a reason for risk, specific measures can also be developed here to eliminate a risk due to the location and to avoid it in the future. Figure 6 below shows the hermitages at risk in Upper Bavaria.

The best practice catalog here also provides ideas for possible usages and the associated necessary thermal energy renovations. In the process, reference is made to the solitary location. For example, a renewable energy supply and space-intensive ice storage systems are far more feasible in listed hermitages than in urban centers. In the future, it should also be possible to quickly identify other boundary conditions, such as traffic connections to motorways or public transportation. The outlook section of this paper provides more information on this topic.

Overall, the system can also be used to quickly and easily record a group of buildings at risk regarding a specific characteristic (in this case, the location). In addition to detailed

**Fig. 6.** Illustration of the interactive map of listed hermitages at risk in the administrative district of Upper Bavaria

information on the individual properties, a quick overview is also possible here. The best practice catalog again considers the characteristics and thus provides specific solutions.

## 5 Conclusion and Outlook

This paper presents an interactive map of Bavaria's listed buildings at risk with an attached best practice database for the rehabilitation of these monuments. Thus, the research gap between systematic data collection and presentation of monuments at risk by a governmental institution and developing a verified best practice catalog for rehabilitating of endangered cultural heritage, is closed. The systematic recording of the endangered building stock enables a statistical analysis. This allows the identification of correlations between boundary conditions such as the type of building, the location of the buildings, the type of construction, and the level of risk. In addition, the systematic overview of the endangered cultural heritage enables the development of transferable solutions for sustainable refurbishment. Besides ecological aspects such as thermal-energetic post-combustion, economic resources such as time and costs can also be saved. On the one hand, the social pillar of sustainability can be strengthened by collecting methods for optimizing comfort, while on the other hand, the overview ensures that architectural monuments that are threatened with extinction do not disappear.

The best practice catalog enables the identification of possible usage options and solutions for sustainable refurbishment, taking the boundary conditions and characteristics of the buildings into account. It is highly relevant that the proposed solutions have been validated. This is often only possible to a limited extent due to the available data. For this reason, the data on the refurbishment of buildings will be documented in more detail in the future, and the building will be monitored after completion. Overall, the digital tool offers the possibility of updating the information, which is highly relevant given the volatility of the data. In addition, the successive expansion of the best practice collection through the digital database is easy to implement.

One critical point is the amount of time required for data maintenance. The actuality of the data must be ensured at regular intervals by comparing it with internet research and interviews with employees in the field of heritage conservation. Due to the dynamic nature of the data, one hundred percent accuracy is never given. The database, therefore, represents a momentary picture subject to uncertainty. Since a higher accuracy can only be achieved with excessive effort, the accuracy is classified as sufficient according to the Pareto principle. One positive aspect here is that the database is created and maintained by a state organization and, therefore, does not depend on voluntary commitment, which can change quickly.

Furthermore, it is important to analyse the potential for creating transferable solutions. In the preservation of listed buildings, the buildings are often unique, meaning that direct transferability is only possible to a limited extent. Nevertheless, the best practice catalog can provide different ideas and directions for use and refurbishment.

As explained in Sect. 4, the database will output location factors such as traffic connections in the future. This data is already stored in the geo-information system, so implementation is possible. In addition to traffic connections, other geo-referenced data, such as flood zones or the location near rivers, can be determined. Such information can significantly influence the concept of utilization and renovation. For example, a listed hermitage with good traffic connections can be used much more easily as an event location than a building without good traffic connections. The riverside location can be used as a renewable energy source, for example.

Overall, the digital guardian provides a quick overview of the endangered cultural heritage and detailed information on the individual buildings. The traffic light system of risk levels clearly shows the actors involved and which objects need to be prioritized, as their loss is imminent.

This digital tool provides a comprehensive database of endangered monuments and a platform for sharing best practice solutions—an essential step towards preserving and protecting the cultural heritage for future generations.

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# Risks and Responsibilities: The German Tendaguru Collection as Cultural Heritage and Its 3D Digitisation

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**Abstract.** The colonial collection of dinosaur fossils, and associated archival documentation from Tendaguru (Tanzania) at the Museum für Naturkunde Berlin is of outstanding importance both in palaeontological and historiographical terms. Along with investigating diverse 3D digitisation methodologies, our research engages with the emerging field of museum collection digitisation from a critical perspective. Current political and public debates on digitisation predominantly view it as a transformatory methodology that renders the museum collections accessible and part of a globally shared heritage. However, while digitisation indeed facilitates wider public access to museum collections, we question the promises of such framing, and highlight its limitations, as well as insist on the importance of critically engaging with the digitised content. Collections in Western museums carry within them layers of colonial narratives and biases. If left unaddressed during the process of digitisation, these colonial terminologies, biases, and violences are transported to the digital world with a wider access to the public than its physical counterpart. Therefore, we point out that while research on the best 2D and 3D digitisation practices is important to enable archiving and documentation of colonial collections, it is equally important to include perspectives that acknowledge the colonial past, and the present responsibilities into these digitisation approaches. We problematise how digitisation has come to be defined as an ultimate solution to inaccessibility and propose alternatively digitisation of colonial museum collections to be viewed as merely a first step in discussing the violent provenance of museum collections.

**Keywords:** Colonial Collection · Tendaguru · Digitisation Strategies · Fossils · archives · Transparency · FAIR and CARE Data Principles


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# 1 Colonial Legacies and the Risks of Digitisation

## 1.1 Introduction

The colonial history of natural history collections has only been publicly debated for a few years. This is all the more astonishing as the connections and lines of continuity that link colonial expansion on the one hand, and natural history collections, knowledge production and museums on the other, are wide-ranging and well researched [1–5]. That the recognition of the violent colonial past of natural history collections can have a transformative potential for museums and collections is, however, exemplified by some institutions that have appointed curators of Indigenous perspectives (for example at Manchester Museum) or brought interdisciplinary research centres into being (such as Humanities of Nature at the Museum für Naturkunde), which refer to the contested past of the collections in their practices, publications and exhibitions. Nonetheless, the majority of Western institutions still lack the human and financial resources to "invest in critical discomfort" [6] and to address the complex and more often than not violent provenance of their collections [7]. In this respect, the situation is still ambiguous: on one hand – in the course of the "imperial turn" in the history of science [8] – methods and results of a critical history of collections are available; on the other hand, many institutions are still reluctant to apply these methods and to research and transparently communicate the colonial past of their holdings. In this situation, digitisation could have the potential to make visible the complex provenance of the collection through a broader accessibility of the objects. However, if the colonial context is left unaddressed and not embedded into a comprehensive interdisciplinary digitisation concept – the colonial biases, violence and terminology are uncritically transported to the digital world.

Using the example of the colonial German Tendaguru collection, which consists of fossils and zoological objects taken between 1909 and 1913 from Southeastern Tanzania, this paper addresses the multiple pitfalls but also the opportunities that go along with digitisation of natural history collections. In the following, we present an outcome of the interdisciplinary research project "Research and Responsibility: Virtual access to integrated fossil and archival material from the German Tendaguru Expedition (1909–1913)", funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) that was launched in October 2023. Acknowledging the complex and also violent history of the Tendaguru collection, this project aims to develop a model for responsible and integrated digitisation strategies that treat archival and palaeontological data as inseparable. In this way, we are creating a virtual collection that can be further researched, enriched and transformed. We lay open the contents of this colonial collection to facilitate global societal and scientific debates and foster dialogues about such multiperspectivic collections.

The project brings together international scholars and practitioners from different disciplinary backgrounds, such as palaeontologists, historians, data and collection managers, data scientists, archivists as well as palaeontological preparators, and so does this paper. It is based on the assumption that research on the best digitisation practices including data, meta- and paradata management is important to enable the archiving and documentation of complex collections. Moreover, we consider it essential to include perspectives that acknowledge the colonial past and address the sensibilities colonial collections require. We therefore propose interdisciplinary integrated digitisation of museum collections of colonial contexts to be viewed as merely the first step in discussing the violent provenance of museum collections, and not the ultimate solution. This paper argues that digitisation is an open-ended process that is informed by dynamic scholarly and public debates and allows for bringing together different perspectives.

### 1.2 Digitisation as Political and Technical Idea

In recent decades, more and more museums and other cultural institutions have been using digitisation processes for their collections. One of the primary factors that makes digitisation of museum collections an appealing endeavour is the possibility of providing wider access to the holdings. The accessibility of digitised cultural heritage artefacts on accessible online platforms can minimise the need to be in the physical space of a cultural institution to engage with the artefact. Democratisation is seen as another key factor of digitisation, as digitisation makes cultural heritage pluralistic by being open to and embracing the different perspectives of people worldwide. The European Commission report on 'Digitisation, online accessibility and digital preservation', frames digitisation as enabling 'unprecedented opportunities' – where the digital cultural heritage could lead to education, research, recreational and other fruitful endeavours [9]. However, digitisation – as much as it is a technical process – is also deeply political in nature. Closely inspecting the process of digitisation, as well as the claims of accessibility and democratisation, illustrates the underlying exclusion and omission that it could be susceptible to. The democratising nature of digitisation is subjected to criticism, such as by Taylor and Gibson [10], who argue that wider accessibility does not equate democratisation of digital cultural heritage. Even if we frame digitisation as an open access initiative that opens up the museum collection to everyone, we have to keep in mind that global access is a big challenge in light of the limited technological infrastructures that some developing countries and countries in the Global South might have [11]. Moreover, legal factors such as licences and copyrights could further limit access to these digital collections [12]. Therefore, digitisation is not proportional to accessibility [13, 14].

Collections in Western museums are often grounded in racial, gender and colonial biases. Digitisation – if performed on these collections from a non-critical perspective – transposes these biases to the digital databases, and further exacerbates them by making data available to a wider public. Kizhner et al. [15] proposes categorisation of the kinds of distortion that could be part of a digital museum collection: e*xclusion bias* occurs when museums select a certain subset of a collection to be digitised. Digitisation, first and foremost, is the process of selection [12]. Exclusion bias leads to certain parts of collections having more visibility, and other parts being excluded. It entails the public – especially the source community – being presented with a pre-selected list of digitised museum objects instead of being offered to define their own selection based on their interest [10]. Another kind of bias that could be entombed in the digital museum collection is the *pre-digitisation bias*. There are violent histories that the museum collections hold within them. Pre-digitisation biases are the entanglements of these different kinds of violences that become part of the digital collection if the digitisation process failed to address them. A digitised museum collection, if mediated only by algorithms and aggregations, can lead to digital cultural colonialism [15]. Being predominantly grounded in the Global North, the majority of algorithms that are in place could lead to further strengthening of biases in the digitised museum collections. These unmediated digital databases and the way they present information play a role in altering the information-seeking behaviour of the individual accessing it. Therefore, in order to inspect these databases from an anti-colonial or feminist point of view requires them to be 'read against the grain', and diverge from the 'normative' ways [11].

Borrowing from *black digital practice*, digitisation needs to integrate human production of knowledge that focuses on social justice, accessibility and inclusion as one of the main goals [16]. Additionally, digitisation should be framed as a tool that could have the potential to lead to further debates on the wider background of colonial exploitation that the Western museums are complicit in – or at the minimum as a technological infrastructure that could enable these debates by transparent communication of the complexities of underlying historical entities.

### 1.3 Colonial Background of the German Tendaguru Expedition

The German Tendaguru expedition took place under the backdrop of brutal German colonialism and at the tail-end of the Maji-Maji war ([5, 17], Heumann et al. forthcoming). It was carried out by the Museum für Naturkunde Berlin (MfN) between 1909 and 1913 in Tanzania, then part of the colony of German East Africa, with the main aim to recover dinosaur material for the museum. Thus, the core of the colonial Tendaguru Collection at the Museum für Naturkunde Berlin is formed by ca. 230 tons of dinosaur fossils, which can be equally regarded as cultural and natural heritage due to their outstanding scientific, political and cultural significance (e.g. [5, 18]). It is flanked by an exceptional and meticulously recorded assemblage of archive materials, such as field diaries, official documents and letters, old specimen labels, as well as photographic documentation of the whole expedition time. Additionally, there are a number of unprepared rock samples with bone material and historical packing containers available in the collections. Together, all of these evidences are an invaluable source of information about the colonial field practices, labour conditions and other aspects of an excavation under colonial rule.

The area around the landmark hill Tendaguru was located within the area of the Maji-Maji War, which lasted from 1905 to 1907 and caused hundreds of thousands of deaths among the local inhabitants [19, 20]. After the European "discovery" of the first dinosaur bones in 1907 (a local worker guided a German mining engineer to the enormous bones) and initial excavations by Stuttgart palaeontologist Eberhard Fraas, the excavation site was exploited under the aegid of the MfN. The director of the then existing Palaeontological Institute of the MfN, Wilhelm von Branca, managed successfully to secure governmental support as well as extensive private donorships for excavations and subsequently sent two members of his institute to the colony [20]. A large number of local workers were recruited in Lindi to dig for dinosaurs during the dry seasons. These workers were instructed in a variety of techniques such as recovering the fossils, documenting them, packaging them, and searching for other finds, and later worked independently at the sites. They were also responsible for translocating the fossils and other collected objects from Tendaguru to the coast in a four to five days long march.

Recent research shows how commonplace colonial violence was at Tendaguru ([21]; Heumann, forthcoming). Not only did racism and corporal punishment define the labour regime, that is, the recruitment, control and exploitation of workers, but violence also defined the extraction of natural resources and local expertise. It is important to note that evidence of these colonial extraction practices is not only documented in the archival photographs and written accounts, but also present in tangible, still unprepared palaeontological objects within the collection, bearing undisputable and re-checkable proof of the uncompromising extractivism of that time. While most of the material at the MfN remained safe, a number of specimens and documentation was destroyed during WWII, when a bomb hit the MfN western wing in 1941. However, the prominent centrepiece of the collection, the exhibit of *Giraffatitan brancai*, has stood intact over the years since its first public display in 1937.

The rich archival material, which is mainly kept in the MfN archive, makes it possible to understand how the excavation was carried out financially, logistically and scientifically, what everyday life was like for the workers and how the recovered fossils were embedded in the subsequent political systems of the Weimar Republic, National Socialism, the GDR and finally reunified Germany. Research into these documents and supplementary oral history interviews have made it abundantly clear that the fossils were far more than meaningless and acultural stones: while there were the first verifiable claims for the return of individual bones to the National Museum in Dar es-Salam in the 1980s [5], the fossils have always been part of cultural practices and customs. They were perceived as "*mali*" ("property"), used for medicinal and agricultural purposes and embedded in local cosmovisions [22]. It is therefore not surprising that voices are also growing louder in Tanzania calling for the collection to be returned and for reparations to be made. Both the colonial history of the excavation and the controversial presence of the collection make it clear that these fossils are both cultural and natural objects [23] that require correspondingly sensitive treatment. In this respect, making such a collection digitally accessible requires first and foremost the involvement of relevant parties from the country of origin, seeking their contribution and consent regarding the contents.

## 2 Digitisation Strategies and Research in the Dinosaur Collection

The project "Research and Responsibility: Virtual access to integrated fossil and archival material from the German Tendaguru Expedition (1909–1913)" does not only focus on digitisation itself, but also includes methodological research and determination of best practices for digitisation projects in a colonial natural history collection with objects of different levels of complexity. With regard to the historical and colonial background of the German Tendaguru collection, we focus our efforts currently on two taxa: *Giraffatitan brancai*, the highly symbolic "trademark" of the German Tendaguru Expedition (1909–1913), and *Dysalotosaurus lettowvorbecki*, a dinosaur taxon with a disputed taxonomic name, and equally symbolic for colonial and postcolonial scientific practices [20]. The number of fossil specimens to be digitised from these two taxa amounts to ca. 1200 bones. Beyond the prepared fossils, we also include unprepared materials, package items, drawings, and storage containers for documentation of colonial field practices (see above).

### 2.1 Dinosaur Fossils

The dinosaur fossils from Tendaguru are scientifically outstanding both in their excellent preservation and in their unmatched diversity, and they are documented from a relatively small area, allowing a broad insight into a 150 Million years old fossil ecosystem. Dinosaurs of different taxonomic groups, as well as of different ecological types have been documented from the Tendaguru collection [18, 24, 25]. Most notable and most disputed (see e.g. [5]) are the iconic finds of skeletal remains of the quadrupedal and plant-eating sauropod dinosaur *Giraffatitan* (*Brachiosaurus*) *brancai*, with the mounted composite skeleton in the exhibition currently with 13.27 m being the highest mounted dinosaur skeleton in the world. Other sauropod taxa from Tendaguru include the rather small species *Dicraeosaurus hansemanni* and *Dicraeosaurus sattleri* [24], the diplodocid *Tornieria africana* [26] and other undetermined diplodocid material (formerly known as "*Barosaurus*" *africanus* [27], fragmentary remains of *Australodocus bohetii* [28], *Wamweracaudia keranjei* [29], *Janenschia robusta* [29], and the large and enigmatic taxon *Tendaguria tanzaniensis* [29]. With the exception of the partial skeleton of *Elaphrosaurus bambergi*, the meat-eating and exclusively bipedal theropod dinosaurs can be proven mostly in form of isolated teeth and single bones in the Tendaguru area [30]. The exclusively plant-eating ornithischian dinosaurs are represented by the quadrupedal thyreophoran stegosaur *Kentrosaurus aethiopicus* and the small bipedal ornithopod *Dysalotosaurus lettowvorbecki* [18]. In addition, the excavations at the Tendaguru area yielded spectacular finds of early mammal teeth as well as number of small vertebrate remains such as fish, lepidosaurs, pterosaurs and fossil crocodiles [25].

### 2.2 3D Digitisation Methods

The chosen digitisation methods and protocols in this project acknowledge the colonial past and biases of the collection as outlined above. Moreover, Tanzanian institutions, communities, civil society actors and scholars were informed and asked for contribution and consent about the contents. We intend to follow a transparent interdisciplinary and dynamic process, in which communication with the scientific community and Tanzanian actors will be an integral component.

We have defined a robust protocol for 3D digitising the fossil objects and computerising the associated data in order to ensure that it is resilient and sustainable over time. To ensure that we have created and backed up all the essential and recommended files to follow best practices in the methodology, we have followed the guidelines outlined by Mallison and Wings [31], Davies et al. [32], Falkingham et al. [33] and Moore et al. [34], evaluating as a first and most important step the preservation intervention points of the project, in order to assess possible risks and to efficiently adapt the digitisation strategies if necessary.

The first steps in a 3D digitisation protocol consist of the recognition and evaluation of the collection and the basic external characteristics of each specimen. This step will help to increase the efficiency of the process. In the specific case of a palaeontological collection, these characteristics include:

- size of the specimen;
- topological complexity (e.g. presence of laminae, ridges, pits, fossae, etc.);
- material appearance (e.g. colour, shine, etc.);
- preservation and general accessibility of the specimen.

The first screening can be done based on the **size of the specimen**. Medium to large specimens (from ca. 5 cm to more than 1 m) are perfect objects for manual Structure from Motion (SfM) photogrammetry ("walk-around" method). If speed is sought throughout the digitisation process, structured light scanners (e.g. Artec 3D scanners) are the best device for digitisation if the specimen has a simple topology. If the fossil has areas of greater complexity, the user can choose to merge the meshes created by scanners of different resolutions (e.g. Artec Eva for the specimen in general and Artec Space Spider for the areas where higher resolution is required), or directly carry out a single SfM photogrammetric project.

*Examples: sauropod appendicular bones, caudal vertebrae.*

If the object is small (from 2 to 5 cm), the user can opt for higher resolution scanners (Artec Space Spider) or SfM photogrammetry using a specific set-up: background of a homogeneous standard colour (black or white, depending on the colour of the specimen), turntable and a camera on a tripod.

*Examples: sauropod skull bones, large Dysalotosaurus bones.*

The **topological complexity of the specimen** is also a factor in the choice of the digitisation technique. Fossils of medium size and a very complex topology, such as skulls, are perfect objects to digitise with the semi-autonomous photogrammetric station CultArm 3D (Fraunhofer-IGD), as the software has an algorithm that helps identify areas that need more photographs to reconstruct their topology. This helps to more automatically and confidently capture the surface of the specimen, avoiding holes in the mesh. This robotic arm is also capable of capturing challenging surface materials (e.g. reflective or very dark surfaces). The main limitation is the time taken to capture each specimen, which can range from 45 min to 2 h depending on the size and complexity of the object. If the user feels comfortable doing SfM photogrammetry (manually or with the turning table and tripod) with these specimens, they should capture in more detail (i.e. more photos, and in different positions/zoom) the complex areas, ensuring that as much of the surface as possible is captured (all accessible areas). Depending on the size of the specimen and the accessibility of complex areas (e.g. internal fenestrae in skulls) the use of the structured light scanner can be considered.

*Examples: medium-to-large skulls, presacral vertebrae.*

Concerning the **material properties of the specimen**, it has been seen that colour can be important in photogrammetry when choosing a background, as there must be a clear difference between the object to be digitised and the background (not being so important in the case of structured light scanners). The brightness of the specimen is also important, as it can produce reflections and glare due to the flash of the camera and the light from the scanners. It is best in these cases to dust to mattify its surface or to use polarising filters in the case of photogrammetry [31].

**Accessibility and preservation of the specimen** are two other factors to be taken into account. If the fossil is fragile, its handling should be avoided, so techniques in which the user is the one who moves around it are the most suitable (i.e. manual photogrammetry or scanners). This applies similarly to fossils that are not mobile, e.g. in exhibition mounts or under protective glass cover. In this case, if the object is in a display glass case the structured light scanner will not give optimal results, so it is better to rely on manual SfM photogrammetry with polarising filters.

**Computed tomography** is the mandatory option when internal volumes are needed, as in contrast to the other methods, volumetric data are generated by this technique. Depending on the size of the specimen, either μCT- or medical CT scanners can be used. As computed tomography is time-consuming and costly, it is only used for specific purposes, such as to capture the 3D morphology of small fossils (e.g. teeth, size below 2 cm), or in case of specific research questions like internal structure reconstruction or fossil preparation protocols.

### 2.3 Data, Meta/Paradata

3D models are exported to common interoperable format types, complying with FAIR Data Principles: .STL, .PLY (ASCII for archival purposes, .bin for online public repositories, e.g. MorphoSource), and .OBJ, plus .png textures. Besides, both RAW and compressed photographs, and the generated scans from the structured light scanners and CT scans will be kept and stored, following the recommendations of Davies et al. [32] and Moore et al. [34].

An important aspect in the meta-paradata capture is the reference to the specimens as being part of a colonial collection, as they were at this time. This means that geographical names, quarries, excavation time and place should be listed as detailed as possible. Equally important, whenever known, the African excavators and workers should be named and associated with the fossils they retrieved from the ground. This is a very important part of the metadata acquisition strategy as these associations will be repeated in data repositories, provide additional information, and are a precondition for the multidisciplinary and multiperspective approach of digitisation we want to follow here.

## 3 Archiving Infrastructure, Access, and Long-Term Data Preservation

### 3.1 Repositories, Databases and Data Access

3D models and their associated metadata are stored across three exclusively functioning repositories – this is done in order to ensure long-term access to archival files, RAW files as well as other data generated during the project. Each of these repositories is specified for certain kinds of data as well as different file sizes. This is also necessary to fulfill the requirements of user-specific download options, computer specifications and capacities of storage, as well as online platforms.

1. All RAW data from the 3D digitisation are stored at the Zuse Institute Berlin (www.zib.de), which has been providing services for the MfN for some years now, for long-term archive and access to the original database.
2. Simplified 3D models, together with their metadata and taxonomic information of the specimen, are uploaded to the research repository MorphoSource (www.morphosource.org), so they are easily accessible and interoperable by any user who could present interest in them.
3. Simplified 3D models are also uploaded to a visualising tool integrated into the research data platform (see Sect. 3.3).
4. All data-meta-para-data are stored in two databases, the collection databases of the MfN. Archival metadata is stored in Actapro and fossil meta-paradata and archival paradata are stored in Specify. Specify has been specially developed to store information covering aspects of colonial heritage and other currently neglected information, as envisaged in our project.

The FAIR and CARE Data Principles are followed to enhance the discoverability, access and reusability of the files [35, 36]. All the created files will be made accessible, and will be brought in context together with the archive material in a research data platform (see Sect. 3.3).

### 3.2 Sustainability and Economies of Digitisation

One of the continuing realities of digital preservation is the amount of storage it requires [37]. As these authors mention, file size is dependent on several factors, including model and source data resolution, and the model creation method. In this project, we provide files of different sizes and complexity levels to allow for the accessibility of both small and larger data packages (see also Sect. 3.1). But this not only implies a storage cost, but also economic ones. An important point in data sharing is financial sustainability, which is mandatory for the long-term preservation of research data [38]. For that, funding bodies, infrastructure providers and publishers are key actors in providing a consistent and easy-to-use environment for FAIR data sharing [39]. The digitisation process and digital data archival of a museum's collection is an immense financial burden; but money spent on data archiving is extremely cost-effective, especially in cases such as this project, where a digital backup of a collection with a colonial background is created and made accessible with all the historical information that surrounds it. Besides, and though the digital storage of this quantity of data implies an important carbon footprint ([40] and references therein), the handling of the physical specimens will be minimised (preserving them for a longer time), and research visits will also be reduced (and so the impact on the climate because of frequent trips to the institution). Moreover, the open access to these 3D models and associated data and metadata allows the long-term reuse of these files by third-party researchers and the creation of new investigation lines, contributing to the development of science [41–44].

### 3.3 Making the Digitised Data Visible on a Research Data Platform

In line with the FAIR Data Principles, it is intrinsic to have the digitised data made widely available to the public in order for it to be findable and accessible. Therefore, all digitised data will be made visible and downloadable through an online research data platform. The motivation behind opting for an online research data platform was to bring together the palaeontological and historical aspects of each specimen into one comprehensive digital corpus. Additionally – as argued before – we view digitisation as the starting point for critical discussion on coloniality of digital collections. The platform could facilitate those discussions by making the historical and scientific aspects accessible. Finally, the research data platform could also have the potential to be further expanded and enriched with more data. Moreover, it will also be developed for further integration of different research perspectives. As a result, the platform could act as a living document that could contain encyclopedic information on the Tendaguru dinosaurs. Another aspect which would be integrated into the research data platform is the detailed documentation of development of the platform as well as of the digitisation methodologies employed during the project. These diverse aspects of the online research data platform will, to an extent, fulfill the meaning of "opening up" a collection without continuing the colonial power dynamics of gatekeeping colonial collections in Western museums.

## 4 Conclusion and Prospectives

Digitising collections with a colonial background is complicated and requires cooperation and shared expertise of specialists of different fields as well as a multiperspective strategy to capture all information available from the data itself. In this chapter we want to point out that instead of viewing digitisation of colonial collections as the ultimate solution to inaccessibility, it can only be a first step to disentangle the different aspects of the colonial past.

As addressed throughout this work, there are a number of theoretical pitfalls on the subject of digitising a colonial collection, and these should be properly weighted into a digitisation concept. These issues comprise the aspects of not making visible the colonial past within the generated data, not reflecting on the methods of digitisation, including a regular check on the digitisation concepts and their amendment. A major problem is the infrastructure and institutional logistics, as well as data security, that could be prone to failure, particularly in times of cyberattacks [45], but also renovations, institutional neglect of the IT-infrastructure, moves of collections and roadwork, as these can contribute to failures in the system. The aim of digitisation is often focused on selecting the "important objects" (i.e. those important for research projects, or those in the best preservational state), instead of showing the mass of material. Finally, financial and temporal issues can hamper the progress of collection digitisation strategies or let institutions opt into "cheaper" solutions that provide less security.

There are however several ways with which to counter these risks. First of all, a proper digitisation concept of a colonial collection would include interdisciplinary discussions on the subject, with a special emphasis on engaging communities from the country of origin of the material to be digitised. This includes also providing information about digitisation plans, asking for contribution and consent about the contents. Data can be linked with their colonial history via meta- and paradata, and this linking should be an integrative step in the digitisation concept and research. Contextualisation of different kinds of data is possible, when work practices and local expertise, as well as in this case the multiple perspectives on objects of being both cultural and natural history objects, are included from the beginning as well as different languages. This includes also a choice for a proper display of digitised data, which needs to go beyond a pure repository. One tool that could be employed for digital representation of the data is through an online research data platform that brings together paleontological and historical aspect of the digitised content. Moreover, transparency about plans and aspects of the digitisation strategy, as well as a constant overhaul of the techniques and plans, allows the digitisation to be viewed as a work in progress with the possibility to enrich and develop the data further. It is very important to provide a financial concept in the beginning that allows supporting such a project through the whole time. Finally, a good digitisation concept needs to include aspects of sustainability, i.e. including long time storage and adequate presentation of the data. Beyond the people doing such projects, institutions holding such collections must be aware of their responsibility and provide support in any of these categories listed above.

We have to be aware that digitisation is is a field of research that is dynamic and ever changing – both in the light of new technology and research, and responsible data practices. When done properly, a digitised colonial collection can provide a valuable basis for further research, scientific and popular dialogue, as well as negotiations with the country of origin, and helps to make colonial collections better comprehensible, easier accessible and more transparent.

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# AI-Driven Analysis in Point Clouds for Archaeological Documentation

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**Abstract.** This paper presents an approach for documenting historical phases in architectural heritage by implementing unsupervised Machine Learning (ML). We employ the RANSAC algorithm for architectural segmentation and K-means to analyze the historical sequence in point clouds using geometric features. Finally, the Extended Matrix (EM) tool within a native IFC environment is used for the archaeological metadata linkage standardization. We have tested our approach using several constructive elements of the San Isidoro complex, in León (Spain).

**Keywords:** unsupervised machine learning · geometric features · stratigraphy · clustering · K-means

## 1 Introduction

Unstructured point clouds obtained via static terrestrial laser scanning consist of a huge amount of data, often underexploited. Processing and managing these three-dimensional (3D) objects are complex, particularly in architectural and archaeological heritage. The historical analysis depends strictly on in-depth methodologies such as Archaeology of Architecture (AA), where stratigraphical analysis is commonly presented through orthoimages and computer-aided design drawings. In such cases, the point cloud is just used for visualization and measurements despite the time-consuming effort required for their generation.

Although many improvements have been made in recent years, integrating archaeological analysis into the Heritage Building Information Modeling (HBIM) workflow remains challenging. Artificial Intelligence (AI), specifically Machine Learning (ML), has been adopted in Cultural Heritage (CH) through the implementation of supervised methods i.e. classification and segmentation of building elements. While computationally less intensive than supervised methods, clustering has not yet been explored for archaeological analysis in point cloud data. This kind of unsupervised ML facilitates the identification of meaningful patterns without labeled data. Clustering is defined [1] as a kind of unsupervised ML that implements the basis of partitioning methods based on similarity and dissimilarity functions. The K-means algorithm proposed by S. Lloyd [2]


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is an example of this approach, specifically a centroid-based clustering that depends on a given number of clusters in the initialization step.

AA is based on stratigraphical analysis to identify the historical and constructive phases of the building. The fundamentals of stratigraphy were established in [3] and then adapted to the implementation of built heritage [4]. In this sense, the information linked to 3D objects is essential for CH documentation and influences conservation guidelines. However, integrating archaeological data in the Industry Foundation Classes (IFC) schema poses specific limitations due to the lack of HBIM standards.

### 1.1 Problem Definition and Contribution

On-site observations and 2D representations comprise archaeological analysis and documentation work. While integrating this data into a 3D environment is time-consuming, the specific conditions of archaeological analysis pose additional challenges. The specific features of historical buildings, i.e. the lack of standardization of constructive elements, the reuse of materials, or the transformations that take place throughout the whole life of the building often hinder interpretation and the automation of tasks. Consequently, point cloud segmentation in the HBIM approach remains a tedious process.

Given the gap of unsupervised ML applications in archaeological documentation, we propose an adapted approach to point cloud analysis. Unlike existing approaches primarily focused on architectural or damage assessment, our approach aims to serve as an initial step that could distinguish historical phases of buildings based on their geometric features. To address this, we first employ the RANSAC algorithm for the architectural segmentation of complex and irregular geometries. Once the architectural elements are segmented, we use the K-means algorithm to group each point cloud into archaeological phases based on its geometric characteristics. After that, the correlation matrix enables the comprehension of geometric feature relationships intended to be generalized for other samples. This method is particularly designed to support the archaeological phase recognition mainly in ashlar masonry walls.

Given that extracting meaningful and tangible information is a key aspect of data mining, the contributions of this paper are as follows: i) Using the K-means algorithm for the Archeology of Architecture approach through the analysis of unlabeled point cloud; ii) combining it with the Scan-to-MesHBIM [5] methodology, which enables obtaining highly detailed 3D objects. These applications have been implemented in the church of the Real Collegiate of San Isidoro (Leon, Spain).

## 2 Related Literature

Recent advancements in the 3D archaeological analysis are demonstrated through tools such as Extended Matrix (EM), a graph language representing the Harris Matrix method. It combines graphic representations and metadata associated with 3D objects for analysis and definition of scientific virtual reconstructions [6]. The protocol developed during the last years and tested in many case studies shows an approach strongly related to virtual reconstruction and dissemination.

Regarding the HBIM methodology, many improvements in workflows and tools have been introduced [7]. Authors in [8–10] have tested the potential of documenting archaeological data in authoring BIM environments. The work presented in [11] enable historical metadata integration into the IFC schema to improve the effectiveness of conservation tasks in HBIM projects, while stratigraphic analysis has not been included. Abate et al. [12] introduced the need to combine EM and HBIM for documentation activities, but metadata interoperability and geometrical issues during the integration are not addressed.

However, the literature analysis shows a lack between the archaeological analysis, currently performed in two-dimensional (2D), and its representation in 3D through HBIM environments. Since its scenario faces the better management of point clouds, many works related to geometrical features, also named shape descriptors, have been performed for specific analysis. The author in [13] has performed exhaustive state-of-the-art AI algorithms for automating BIM modeling processes based on point cloud data. Implementations of supervised ML algorithms in HBIM approaches include Random Forest [14] or k-nearest neighbors [15], providing good results in the recognition of architectural elements. Other authors [16] have proposed a classification method related to decay according to a range of wall defect types on point clouds. Their method based on two-dimensional (2D) Continuous Wavelet Transformation (CWT) identifies in the point cloud the constitutive units (stone blocks and mortar regions) and then, using supervised ML, these are classified according to decay type.

Nevertheless, the issues about time-consuming labeling tasks with supervised ML have already been highlighted in [17]. In the field of Unsupervised ML, the work presented in [18] has analyzed the clustering algorithms: strengths and weaknesses, comparison, and potential directions. The K-means algorithm has been reviewed for its variety and spread in many fields [19], including extensions such as U-k-means [20], which finds the number of clusters without knowing a priori the optimal $k$. In [21] the K-means algorithm has been incorporated to improve the accuracy and optimization of point clouds. Modern Clustering algorithms are more developed and powerful. In the work presented by [22], a novel weighted kernel K-means algorithm that integrates aspects of spectral clustering is developed, improving computational efficiency and maintaining accuracy in clustering tasks. While these works have improved the data processing of historical assets, they have not solved the problem of archaeological documentation using point clouds in an HBIM workflow.

## 3 Proposed Method

The method proposed for historical documentation using point clouds is divided into three main steps. First, after preprocessing the PCD, architectural segmentation is performed using the RANSAC algorithm. In the second step, geometric features are selected, calculated, and normalized to prepare the data for subsequent analysis. Finally, K-means is applied to cluster the points to guide the 3D meshing step.

### 3.1 Automated PCD Segmentation Using RANSAC

The Random Sample Consensus (RANSAC) [23] is a model-fitting algorithm. It iteratively selects random subsets of points to model the geometric shape of the plane. It searches for the optimal normal vector $\overrightarrow{n}$, which maximizes the number of inliers within a given distance threshold ($\epsilon$). The process continues as follows:

$$P_i = \arg\max_n \sum\nolimits_{j \in C} \left( \frac{|d(n, p_j)|}{\vec{n}} < \varepsilon \right) \quad (1)$$

where $P_i$ represents the set of inliers corresponding to the plane $i$. This set contains all the points that fit the identified geometric model. Outliers cannot be considered since they may represent additional geometry.

The use of RANSAC in architectural heritage is limited to the presence of complex architectural shapes, but its implementation, as commented before, is well-known in scientific literature. However, HBIM approaches do not include it often since parametric and other kinds of modeling are more used during the 3D meshing step, omitting PCD segmentation.

### 3.2 Point Cloud Feature Engineering

In a point cloud $P$, each point is represented by its Cartesian coordinates x, y, and z, related to an established origin. However, each point can hold other values such as geometric features $p_i = \{f_1, f_2, f_3 \ldots f_n\}$, where $f_i$ defines the feature value of a point in a space. Defining reliable features is crucial for archaeological phase recognition, where redundant or irrelevant information can be filtered. The geometric features are inherited data properties that define distance and similarity measurement [24] and include roughness, planarity, linearity, verticality, omnivariance, eigentropy, and the 1st, 2nd, and 3rd eigenvalues. Eigenvalues are mathematical concepts utilized for analyzing behavior, linear transformation, or matrices, providing insights into the distribution of points along different axes or dimensions.

Separately, RGB values can be considered only if good lighting conditions exist. The local neighborhood radius is analyzed for each 3D point in the point cloud establishing a distance-based criteria, and the covariance matrix is used to extract these geometric features. This filter-based feature selection method is applied using the Euclidean distance, a proximity measure that will be extremely presented during the entire process. If point $p_i$ is given by its coordinates $X_i$, $Y_i$, $Z_i$ and point $p_j$ is given by its coordinates $X_j$, $Y_j$, $Z_j$, the Euclidean distance can be calculated as:

$$d(p_i, p_j) = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2} \quad (2)$$

**Normalization and Log Transformation.** Data normalization involves transforming raw data features to be on a similar scale, affording more stability to the model and robust calculations. Features that consist of large scales can be more dominant than others during the distance calculation, producing distortional results [24]. Histogram shapes are heterogeneous, requiring different normalization techniques for subsequent analysis. For example, the histograms that are close to bell-shaped distribution may be normalized via scaling to the range, also named the min-max normalization method:

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (3)$$

where $x'$ is the scaled value, x is the original feature value, $x_{min}$ is the minimum value in the dataset, and $x_{max}$ is the maximum value in the dataset.

### 3.3 K-means Clustering

After normalizing data, accurate similarity calculation between variables is possible. Quantitative input features are utilized in a K-means clustering algorithm to obtain qualitative values. Hyperparameters are defined to control the behavior of the K-means algorithm, which is considered a crucial step for achieving meaningful results.

**Initialization: Random Centroids Selection and Point Assignment.** When choosing the initialization method, the rest of the hyperparameters that should be defined are the number of clusters, maximum iterations, tolerance, and precomputed distances. In the input data the vector $K = \{K1, \ldots, Kn\}$, the integer parameter $k = n$ is the number of the vector elements. Once the number of clusters is defined, each cluster's centroid $\theta_k$ is randomly determined. After this, points are assigned to each closest $\theta_k$ calculating the Euclidean distance of each point to each centroid. The data space is partitioned into regions as Voronoi cells, closest to a particular centroid.

**Optimization: Cluster Re-assignment.** As the centroids shift, the algorithm reevaluates each point selected. Points are assigned to the closer centroid, creating new clusters. This iterative process continues until the data points no longer switch clusters between rounds (it will be refined until they do not change significantly). This process helps to mitigate any bias introduced by the randomness of initial centroid selection. The distance calculation for point assignment is obtained again through the Euclidean distance, and in this stage, it will determine which cluster centroid is closest to each point.

## 4 Experimental Results

In the following section the RANSAC and K-means algorithms are applied for historical documentation in the Real Collegiate of San Isidoro in León, Spain. This implementation, including preprocessing steps, has been conducted on the Google Colab platform through the NumPy and Open3d [25] Python libraries. The final step is to generate 3D surfaces from the PCD analysis into an HBIM project. The test has been carried out in Bonsai, the former BlenderBIM [26], which allows working with native IFC.

### 4.1 The Archaeological Sequence of the Real Collegiate of San Isidoro (León, Spain)

The Real Collegiate of San Isidoro, in León (Spain), is a complex of buildings that dates back to the 1st half of the 11th century when a pre-Romanesque building was erected over the Roman walls of the city. It comprised a church and, at least, two adjacent spaces on the west side: the Pantheon (lower floor) and the Cámara de Doña Sancha (upper floor). The church was partially demolished to build a bigger Romanesque Basilica over it, completed in the 12th century, and the only remaining part of the previous church is the west end. Our work then focuses on the part where the pre-Romanesque pantheon and church relate to the 12th-century Romanesque Basilica.

This area has been analyzed with the methodology of the AA so that its division into historical phases is already known and it is possible to compare it with the results of our analysis [27]. The rich historical sequence of the building directly affects its geometrical features. These spatial properties are chosen to perform our analysis in two specific areas of the complex, as Fig. 1 shows. Santoni et al. [10] is considered the first HBIM implementation, taking special attention to the historical dataset and serving as the baseline for the presented contribution.

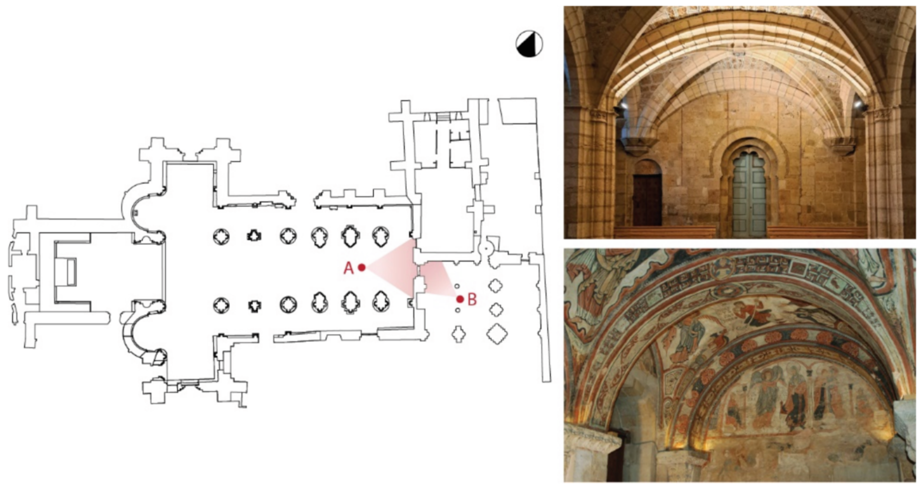


**Fig. 1.** Floor plan of the San Isidoro complex, highlighting the location of the areas (in red) selected for our tests: A) the church's west end bay (top right) and B) the pantheon (bottom right).

### 4.2 RANSAC and K-means for CH Documentation

Preprocessing consists of different tasks to prepare the input point cloud data. This step includes statistical outlier removal and decimation. Then, the normal computational step is performed to ensure it reflects true surface geometry. These aspects are critical for preparing the data for subsequent analysis.

At this point, the RANSAC algorithm is implemented to detect dominant planar features with a segmented portion of the point cloud. Due to the initial stage of the research, only the walls of the selected areas (see Fig. 1) have been considered since they represent the historical sequence of the building better than other architectural elements. A distance threshold was applied to identify inliers for each candidate plane, followed by a filtering stage to discard planes supported by an insufficient number of points. To ensure spatial distinctiveness, a centroid-based comparison was introduced, preventing the detection of redundant or closely overlapping planes.

This method enables the isolation of geometrically significant planar elements, providing a reliable basis for subsequent historical and architectural analysis. Figure 2 depicts the outcome regarding the walls that will be subjected to archaeological analysis. Both cases represent different geometrical conditions, decoration, and states of preservation. For this reason, they are considered good samples for testing K-means capability in various scenarios.

**Fig. 2.** Results of the RANSAC shape detection algorithm applied to the San Isidoro complex: The selected areas have been processed to extract the architectural elements.

The feature engineering step determines which features will be selected, extracted, and used in the training model as input. In our case, RGB values have not been considered for this implementation due to the extreme lighting conditions in indoor religious buildings affecting color gradients. The process begins with the normalization step using the NumPy library. Following feature extraction, the distribution of the nine geometric features was analyzed in both walls. Due to the observed heterogeneity in the shapes, the min-max normalization method was employed in subsequent analysis.

The geometric features mentioned represent some anomalies that correspond with different interventions performed on the wall. Figure 3 represents the normalized histograms of the selected features, surface variation, and verticality, and the point cloud visualization calculated considering a 4 cm neighborhood radius in *Wall_01* and 8 cm for *Wall_03*.

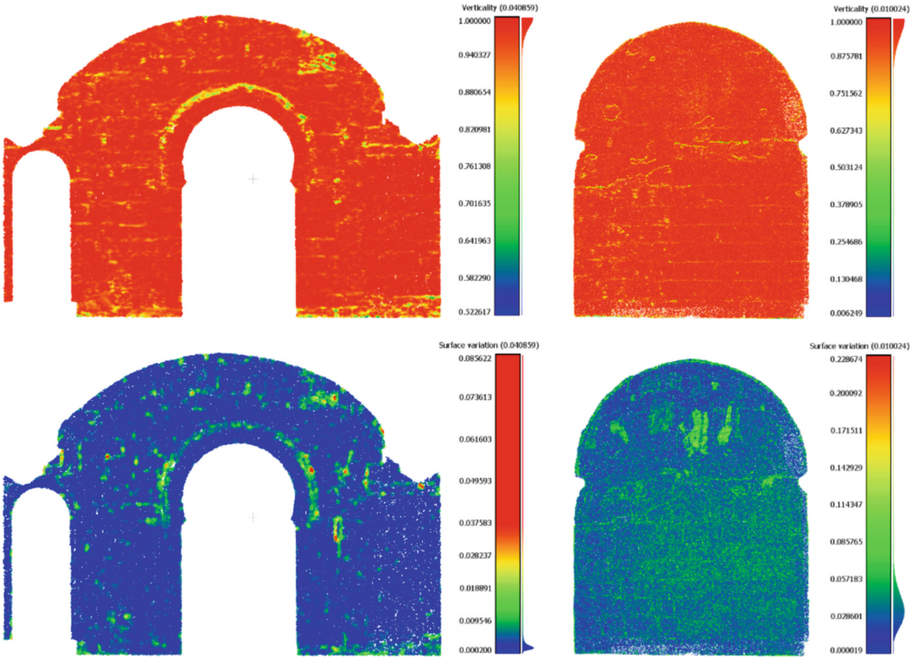


**Fig. 3.** Calculation of verticality (upper part) and surface variation (bottom part) in *Wall_01* and *Wall_03*.

Before applying K-means clustering, the correlation matrix was performed and can be checked in Fig. 6 (Appendix 1). This calculation shows the relationship between the features, in this case, the correlation coefficients offering a standardized measure of the variable's relationship.

**Clustering Results and Validation.** Using the Python library Scikit-learn, K-means clustered in three groups the point cloud of *Wall_01* and in two the *Wall_03*. This generates some inconsistencies according to previous historical analyses [27]. In any case, these clustering results must be evaluated based on various metrics, including 1) cluster cohesion and 2) cluster separation, which refers to how distinct clusters are from each other. To assess cohesion, the Elbow Method was employed by analyzing the inertia, a distance-based metric that measures the Sum of Squared Distances (SSD) between data points and their respective centroid. K-means aims to minimize this value aiming for well-defined and compact clusters.

Figure 7 (Appendix 2) shows the SSD values obtained for varying numbers of $k$ in *Wall_01*. The Elbow method helps to identify the point at which adding more clusters no longer significantly reduces the SSD, thus indicating the optimal number of clusters.

Figure 4 shows the comparison between our analysis and the result of the previous archaeological research. Some areas represent different geometrical feature values that could belong to the historical phases recognized by archaeologists in previous works. Although recognition is not so precise, the result could highlight potential variations in the sequence of transformations of the building.

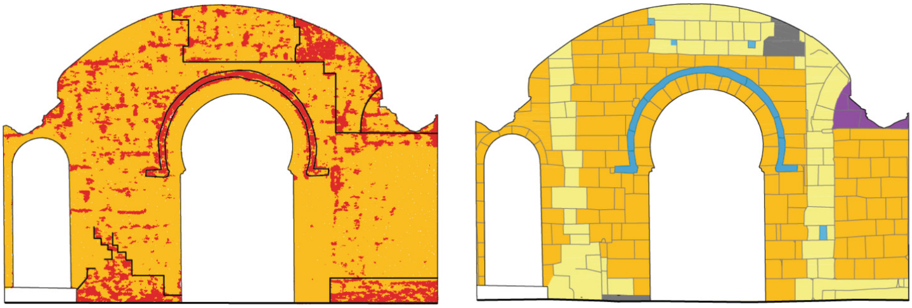

**Fig. 4.** Results of the archaeological phases clustering (red points) applied on *Wall_01* (on the left) and previous archaeological analysis carried out in 2D (on the right).

The historical phase clustering is followed by segmenting the values related to each historical phase, requiring manual corrections since the results are noisy. Then, the 3D meshing step is performed to obtain 3D surfaces with a high level of accuracy. This approach, framed in the Scan-to-MesHBIM methodology, stresses the point cloud and avoids manual modeling.

### 4.3 Integration into the HBIM Project

In a native IFC schema environment, 3D objects represent different subtypes of *IfcBuildingElement* and posterior phases are integrated as *IfcSurfaceFeature*, a solution already implemented in previous works [11] for decay analysis. In this way, an *IfcWall* represents the geometry of the original phase preserved, while the following phases are associated with the object as *IfcSurfaceFeature*.

With our approach, archaeological metadata is manipulated through EM and then integrated into the IFC Schema using the A$^2$Heritage[1] data library capabilities. These data are stored on each 3D object using tailored property sets created to be used in different CH contexts. Each architectural element contains the archaeological phase color as a material, preserving at the same time the RGB values from the point cloud and enabling a realistic scene visualization. The EM tool links geometry to each stratigraphic unit (Matrix Harris) through the yEd Graph editor without affecting IFC data. Figure 5 simplifies the approach of integrating archaeological data into an HBIM framework. Given that the model has preserved the vertex color from the point cloud, it is possible to switch to a realistic view without duplicating building element entities, a commonly presented issue in scientific literature that affects the efficiency of the IFC schema.

[1] The library is accessible for other HBIM users through the following repository: https://github.com/jmc-96/Architectural-Archaeological-Heritage-IFC-Data-Library.

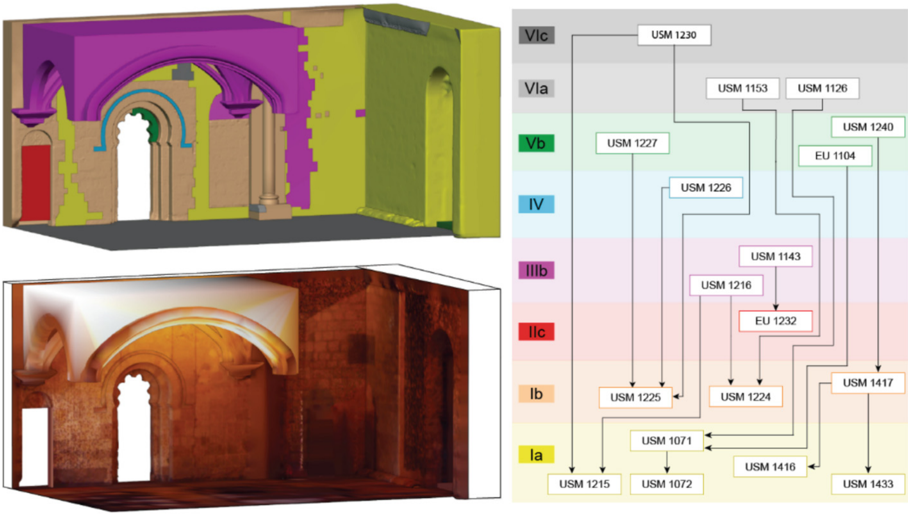


**Fig. 5.** San Isidoro HBIM project: On the left, the archaeological phase view (upper part) and the architectural one (lower part); On the right, the Harris Matrix performed in yEd is linked to 3D objects in the IFC schema.

## 5 Conclusions and Discussion

This study presents a clustering implementation on a point cloud for historical documentation avoiding hand-labelled steps. The paper demonstrates how combining geometric features reflects the degree of change on the point cloud's surface, and, in some areas, it highlights the transformation sequence of the historical building. The method was applied to two walls, a roughly flat element where geometric variations could correspond to different historical phases. In contrast, the clustering is not completely accurate, making necessary some light corrections before the 3D meshing process.

In further experiments, including RGB values should allow us to assess their reliability under favorable lighting conditions. The presented analysis could help the onsite work of archaeologists, so it assesses a tool that could be a useful complement for professionals in some cases. Our aim is not to substitute the on-site analysis of archaeologists but to facilitate and improve it. In this experiment, we tested the algorithm's limitations under these conditions, given that K-means assumes spherical and equal-sized clusters instead of arbitrary shapes. As the problems of funding non-convex clusters may not always hold for archaeological data, other clustering algorithms such as k-medians, k-medoids, or the Gaussian mixture model may be considered in future tests.

The point cloud analysis supports the aims of the Scan-to-MesHBIM approach since it provides the group of points considered as archaeological phases. This scenario allows the implementation of automated 3D meshing steps of each historical surface associated with the "original" wall. With the proposed framework, an HBIM project has been developed and enriched with archaeological data. K-means appears as a partner for the early step of the analysis, guiding the expert to a deeper understanding of the element's historical evolution and then allowing the user to make driven decisions.

**Disclosure of Interests.** The authors have no competing interests to declare relevant to this article's content.

# Appendix 1

Correlation values are commonly filtered between high positive, moderate positive (0.3 to 0.7), low positive (01 to 0.3), non-correlation (–0.1 to 0.1), low negative (–0.1 to –0.1), moderate negative (–0.7 to –0.3) and high negative (–1.0 to –0.7). The correlation between roughness, omnivariance, and verticality is considered as moderate.

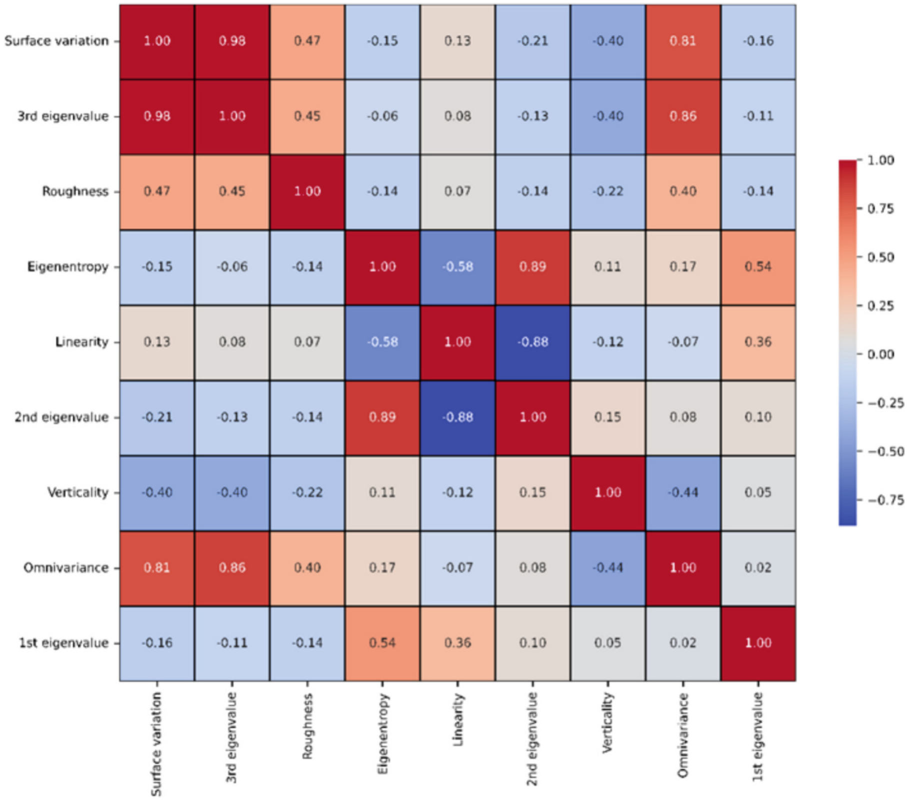


**Fig. 6.** Correlation Matrix of the entire list of geometric features stored in the point cloud of *Wall_01*.

# Appendix 2

Additionally, different cluster results are shown in Fig. 7. From top to bottom, each raw represents different calculations obtained in *Wall_01*: roughness and verticality, roughness and omnivariance, and omnivariance and verticality.

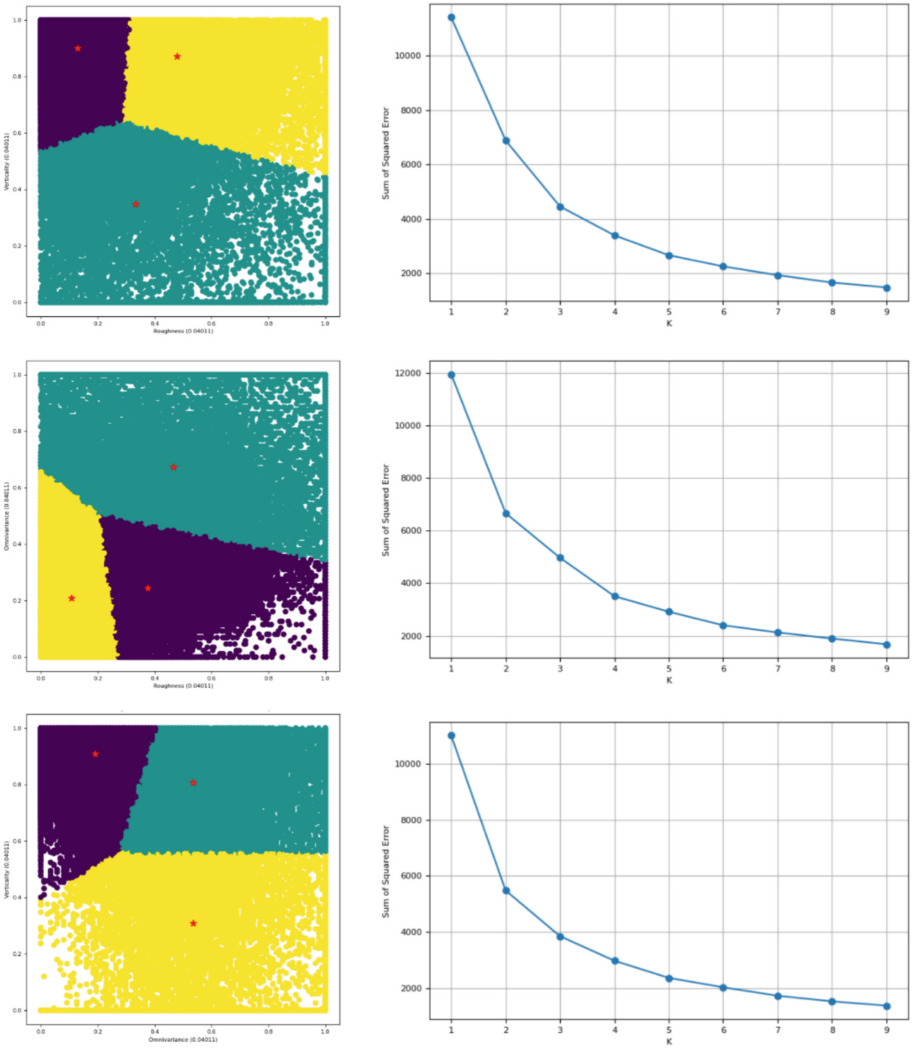


**Fig. 7.** K-means implementation. On the left, the plotted clusters. In the right, the elbow method determines the optimal $k$ number.

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# Digital Preservation and Restoration of Historic Buildings in Agadez, Niger

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**Abstract.** Niger possesses a rich cultural and historical legacy, largely due to its abundant archaeological and paleontological sites. Research from the 1970s emphasized the importance of areas like the Ténéré plain and the Termit region, potentially centers of technological advancement in iron and copper metallurgy. Agadez, situated on the ancient trans-Saharan trade route, gained UNESCO World Heritage status in 2013. The city is famed for its traditional mud-brick architecture and landmarks such as the Great Mosque of Agadez, notable for its 27-meter tall minaret. However, Niger's heritage faces significant challenges from Sahelian unrest and climate change, impacting nomadic communities and causing destructive floods in Agadez. Intense precipitation and strong winds exacerbate soil erosion and the shifting of dunes, endangering historical structures. Preservation efforts include documentation and restoration initiatives, notably through 3D digitization. Supported by the ALIPH foundation, the Imane-Atarikh and Iconem project aims to document and restore Agadez's historic core. Restoration campaigns focused on endangered structures, using traditional methods to conserve historical buildings. The project generated detailed 3D models and orthophotos of the Great Mosque of Agadez, featured in a scientific journal and presented at the International Alliance for the Protection of Heritage in


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Conflict Areas forum. Rehabilitation efforts encompass various neighborhoods of Agadez, emphasizing structural reinforcement and architectural enhancement, guided by collaboration between Imane-Atarikh, Iconem, and the local community. Notably, the initiative has empowered women and gained support from local authorities, receiving extensive coverage by local journalists and involving educational programs.

**Keywords:** Niger · 3D digitization · House restoration

## 1 Introduction

Niger has a rich cultural and historical heritage, including numerous archaeological sites [7,31,34] and paleontological sites [28,40]. For instance, in the 1970s, prehistorians and geologists from ORSTOM studied the relief features bordering the Ténéré Plain, particularly the eastern Air and the regions of Fachi and Bilma. In 1972, a systematic campaign took place in the Termit Massif, located between southeastern Air and Lake Chad, marking a transition zone between the desert and the Sahel, primarily used as a passage for camel caravans with no permanent villages. Between 1976 and 1981, research in southern Sahara in Niger reignited interest in metallurgy, building on earlier discoveries at Termit [31,34]. These studies suggested that this region could be a center of innovation with various technological phases for iron and copper.

The city of Agadez, situated at the southern end of the Aïr Mountains and on the southeastern fringes of the Sahara Desert, has long been a key stop on the eastern trans-Saharan route, linking the Maghreb to the Sahelian region between the Niger River and Lake Chad [3]. Perceived as the “gateway to the desert” and participating in the Saharan “salt route,” Agadez is now the largest city in the region and the capital of northeastern Niger. Its old city has been listed as a UNESCO World Heritage site since 2013 [38], and its population was estimated to be over 500,000 in 2017 [39]. The ancient city, the heart of the present-day city, consists of 11 irregularly shaped neighborhoods, remnants of the old camps of Tuareg tribes. A major north-south thoroughfare, established during colonization, divides the city into two parts. These neighborhoods still form the administrative framework of the historic city, including Katanga, Amarewat, Amdit, Imourdan-Magass, Imourdan-Nafala, Akanfaya, Oungoual-Bayi, Agar-garin-saka, Founé-Imé, Obitara, and Hougoubéré. Agadez’s architectural heritage, dating from the 15th and 16th centuries to the early 20th century, consists of traditional adobe houses (banko) [21], organized around inner courtyards and with few exterior openings to protect from the sun. The constructions include flat roofs and doors often flanked by earth benches. Among the construction materials, clayey earth predominates, used in the form of conical or rectangular bricks. The traditional house typically has a versatile entrance vestibule and is organized around a central courtyard. Agadez’s historic city boasts 18 major sites, including the Sultan of Aïr’s palace, dating from the 15th century, and the Great Mosque of Agadez, an emblem of Niger with its 27-meter minaret.

Two other 16th-century mosques, the house of the judge (cadi), the palace of the Anastafidet, the house of Sidi Kâ, the residence of Sultan Almoumine, the house and butchery of Ati Sarkin Fawa, and the Hotel de l'Aïr, built in 1917, complete this rich heritage [42].

To summarize the main lines of the city's history, the first settled inhabitants of Agadez in the 11th century were the Hausa people, who migrated from the south attracted by the water springs at the foothills of the Aïr Mountains [3]. While retaining some animist traditions, the Hausa people adopted Islam and developed refined mud-brick architecture, later adopted by the Berbers and then the Tuaregs. In the early 15th century, the Tuaregs established the Sultanate of Aïr, controlling the Saharan southeast caravan trade and settling in Agadez during the reign of Ilisawan (1430–1449) [26]. This marked the beginning of sedentarization of Tuareg nomadic tribes, transforming Agadez into a capital and significant caravan center where Muslim traders and intellectuals converged. The sultanate's power consolidated in the 16th century, embellishing the city, notably with the construction of a remarkable minaret by Zakarya [4], a revered builder sheikh, who also erected two other mosques. Despite conflicts with the Songhai Empire [23] and the Berber kingdom of Takedda [10], Agadez gained recognition in the West through Leo Africanus (1526) [33]. Subsequent centuries saw the city face epidemics (1687–89) [26] and invasions, notably by the Kel Away (1740) [36], leading to enduring insecurity exacerbated by Tuareg tribal conflicts in the 19th century, impacting the architectural heritage. In 1904, French troops took Agadez but faced the Kaossen rebellion supported by the Sultan of Aïr (1916–17) [2]. Despite temporary deposition, the sultanate was reinstated as an intermediate power. Upon independence in 1960 [15], the Sultanate of Aïr maintained its crucial sociopolitical role. In the 1980s, uranium mining and the opening of the Niamey - Arlit road [30] gave a new impetus to Agadez. The current population is a blend of "sultan's people," descendants of Tuareg tribes and their slaves, and Arab merchants. The "sultan's people" include the Sultan's close associates and administrators such as the Dangaladima [35], vice-sultan, the cadi Tourawa [14], and the Magagia, in charge of women's affairs [20]. They also hold economic functions such as organizing markets and managing butcheries. Annually, the Sultan performs a ritual procession around the city, invoking peace, security, and prosperity. Agadez is distinguished by its numerous squares, originally meant for trade and social gatherings. House construction, overseen by the maghalami, a knowledgeable master mason, involves religious rites and symbolizes family continuity. The maintenance of the minaret [12], a ritual task overseen by the master mason under the Sultan's supervision, involves students from Quranic schools. Formerly a major artisanal center, Agadez retains significant craft activity in certain neighborhoods, producing pottery, leather boxes for incense, and iconic jewelry like the Agadez cross [19]. Music, songs, and dances, blending traditions from various city communities, address diverse themes such as love, honor, politics, and war, remaining highly popular with typical regional instruments [44]. The historic heart of Agadez today is inhabited by residents whose incomes have been significantly affected since the decline of tourism, which was once prevalent. The ongoing security issues in the Sahel over the past decade pose a direct threat to Niger's heritage [5,25,37]. Nomadic pastoralists face numerous climatic, political, and economic constraints, compounded by insecurity and the encroachment on pastoral lands, notably due to international mining exploitation. African borders, often seen as scars of imperialism, also result from complex and negotiated local dynamics.

In addition a second threat emerges: massive floods [13] exacerbated by strong winds [1,41]. The 'Sahel hydrological paradox' describes increased runoff despite drought, attributed to soil degradation from agricultural practices and weakened vegetation. Recent data indicate rising extreme precipitation, intensifying this phenomenon in the Middle Niger Basin, a severely affected semi-arid zone since post-1968 drought. A study on livestock in Filingué, Niger, reveals that herders perceive climate change as a threat to their practices, adopting adaptation strategies such as transhumance and forage storage [22]. In the Manga region, wind erosion of active dunes, influenced by wind speed, demonstrates increased mobility of unfixed dunes, requiring a nuanced understanding of their spatio-temporal dynamics. Climate change has disrupted seasonal patterns, causing these floods to occur more frequently and earlier than in previous years. Since the advent of satellite measurements, numerous missions like Megha-Tropiques focus on monitoring the atmosphere and land surface, particularly to assess tropical zone precipitation. This study, centered on the Niger River, highlights the potential of satellite precipitation estimates for flood monitoring, emphasizing error structure in hydrological modeling and the influence of land surface changes and precipitation on floods since the 1950s [11]. The city of Agadez has suffered severe floods [16], damaging its heritage. These disasters present numerous challenges for effective emergency response and community sustainability, exacerbated by limited resource availability, the need for coordinated aid distribution, and involvement of various organizations, especially at the international level [18]. Agadez's traditional architecture is particularly vulnerable to these meteorological and environmental threats. Given the scale of these phenomena, urgent documentation, including 3D digitization, was necessary to consolidate and restore some of the structures, as well as to provide tools to better understand the patterns of destruction and improve the site's management strategy.

## 2 Method

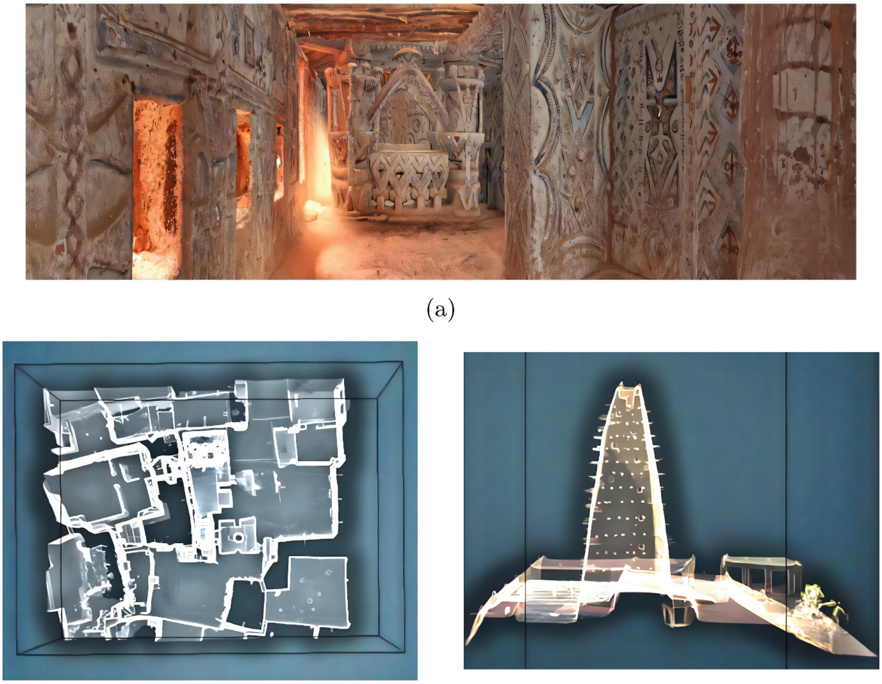
The project management was conducted by the association Imane-Atarikh, which means "Life and Heritage" in Tamasheq, a Tuareg language. The 3D scanning was performed by the company Iconem [27,29], a startup known for its contributions to preserving endangered World Heritage sites by creating their digital 3D replicas. Iconem relies on satellite image analysis and 3D photogrammetry to carry out multiscalar analysis of heritage environment [32]. The funding for these operations was provided by the Aliph Foundation. Established in Geneva on March 8, 2017, the ALIPH Foundation aims to protect cultural heritage threatened by conflict and climate change, fulfilling commitments made at various international conferences, including those of UNESCO and the Abu Dhabi Declaration. ALIPH, funded by several states and private donors, intervenes to prevent, secure, and restore endangered heritage, launching its first call for projects in January 2019 [8,9]. A preliminary field mission occurred in March 2020 to assess needs and conduct an initial capacity-building session. It quickly became apparent that creating essential architectural documentation to record heritage data and developing a restoration strategy for the most damaged structures in the historic center were crucial. The initial goals included digitizing the site by acquiring 3D photogrammetric data of some heritage structures and producing architectural documentation for selected buildings. Additionally, conservation and restoration efforts were planned, such as plastering five houses, repairing and reinforcing house walls, plastering the hangar of the Great Mosque, rehabilitating the women's lodges and other sections of the Great Mosque, and establishing training programs and job opportunities for local youth, especially in masonry.

### 2.1 3D Digitization

In the course of an initial trip in February-March 2020 to meet with local representatives and structure the program according to their needs, Iconem used 3D photogrammetry to capture several 15th-century Sahelian city buildings, including the Great Mosque and its 27-meter adobe minaret, the tallest in West Africa. Data acquisition was carried out for external and internal spaces of the structure. Additionally, two local representatives were trained in these documentation techniques to ensure project continuity. Two other photogrammetric survey campaigns allowed the digitization of other buildings, including artisan and merchant houses. In July 2020, preparatory work and theoretical and practical training took place, followed by weekly sessions with Iconem. The process resulted in the creation of precise millimeter-scale point clouds (cf Fig. 1(a), (b), (c)) and detailed architectural documentation from several thousand photos, covering the Great Mosque, the Abawagé house, the Madigou Mohamed house, the Baker's house, the Moussa Yahya house, and the Alfijia house.

### 2.2 Building Rehabilitation

Rehabilitation efforts for old mud houses in Agadez primarily focused on restoring iconic structures like the great mosque and historic homes, as well as vulnerable dwellings. The Imane Atarick association and its partners spearheaded these efforts, guided by principles of preserving earthen architectural heritage and addressing climate change challenges. They successfully rehabilitated the first 20 houses and transferred traditional conservation skills to young people through training in masonry techniques. Interventions were tailored to each house's condition, addressing issues such as crack repair, surface treatment, wall base reinforcement, roof and acroterial wall reconstruction, slope correction, and



(a)

(b)

(c)

**Fig. 1.** Point cloud of the interior of the baker's house (a), its complex (b), and the minaret of the mosque (c) ©Iconem.

replastering. The buildings selected for rehabilitation were identified by community representatives, in collaboration with the town's administrative and traditional authorities, including the Sultan of Aïr, district chiefs, the Agadez Town Hall, and CECOGAZ. In the project's first phase, the team identified several habitats, choosing 20 houses based on their vulnerability and the precarious living conditions of the inhabitants, as evidenced by site photos. These houses, all of historic value, exhibited advanced pathologies, with some at risk of collapse. The project focused on densely populated historic districts like Amarewat, Founem, Oungoual Bayi, Akanfaya, and Agargar, which featured narrow alleyways inaccessible to supply trucks and carts. Local masons executed the work using materials and techniques suitable for the environment, aimed at preserving and enhancing the houses nearing collapse. Young residents of the rehabilitated houses were trained in earthen architecture conservation techniques, ensuring knowledge transmission to future generations and maintenance of these practices. The detailed work schedule for each house included: preparing earth for adobes (3 days), constructing mortars (14 days), exterior plastering (3 days), brick making (1 day), debris removal and excavation (1 day), surface preparation for masonry corrections (1 day), crack repair (1 day), reinforcing wall bases (1 day), rebuilding the parapet (1 day), installing gutters (1 day), applying three coats of plaster (2 days each), repairing and installing doors and windows (1 day), and landscaping and cleaning the courtyard for water drainage (1 day) (see Fig. 2(a)).

The neighborhoods were densely packed and hard to access for construction work. Some houses were unreachable by truck, necessitating manual transport of materials. Human resources included master masons, assistant masons, 20 apprentices training in historic building rehabilitation (see Fig. 2(b)), and local workers. Material resources included wheelbarrows, shovels, picks, reinforced water supply connections, ladders, scaffolding, molds, buckets, paint cans, rakes, and barrels. Materials used were earth, sand, wood, poles, straw, manure, and water. The second phase of the project involves rehabilitating 30 houses in the old town of Agadez during 2023–2024. Work is ongoing, with sixteen houses completed and four more in progress. This phase includes roof maintenance and sanitation of gutters and septic tanks. The second phase also targets houses at risk of collapse that are of historical significance, preserving relics of past generations for present generations. Manuscripts preserved in the mosques of Agadez [43] were vulnerable to climate and insect damage. Initially, about twenty very old manuscripts, some handwritten, were catalogued in the Abawaj mosque to protect them from termites and rodents. Local craftsmen were recruited to create bespoke leather bags, specially treated to house these manuscripts (cf Fig. 2(b)). The bags, carved and decorated to resemble ancient protections destroyed by termites, were presented at a ceremony attended by district chiefs, the sultan's representative, and marabouts. The restoration of traditional drums in Agadez [26] involved several essential steps: initial assessment of the drum's condition, dusting, repair of the wooden frame, replacement of the skin, treatment of the decorations, and application of preservatives to protect the instrument. Maintaining the authenticity of the object was crucial, involving consultation with local experts and documentation of each stage to preserve the cultural heritage, particularly for the Bianou festival [6].

## 3 Results

### 3.1 3D Digitization

Sections within point clouds and 3D meshes were extracted from the pointcloud to provide different views, along with an orthophotograph of the Great Mosque (see Fig. 3(a)). A video showcasing the 3D scans (see Fig. 3(b)) was also produced to highlight and document the extensive 3D scanning efforts. This video was notably screened during the ALIPH conference held on March 6th and 7th, 2023, at its inaugural forum in Abu Dhabi, organized by the Department of Culture and Tourism – Abu Dhabi (DCT – Abu Dhabi) and the foundation [17].

### 3.2 Building Rehabilitation

The initial phase in 2021 rehabilitated 20 houses (cf Fig. 4) and conserved the great mosque. This project enhanced cultural heritage value. It also improved

(a)

(b)

**Fig. 2.** (a) Some steps of the restoration process/(b) Training session, making leather bags and protecting a manuscript

young people's skills in local construction. Furthermore, it contributed to the socio-economic and cultural development of Agadez.

During the association's initial heritage conservation efforts in Agadez, several actions were taken. In Amarewat, a Koranic school received plastering and reinforcement of walls, roofs, and parapets. Additionally, two houses had their foundations and walls reinforced, and a rainwater drainage pit was installed. In Foun, a house was decorated, and its roof and brick parapets were redone. In Akanfaya, a house had its facades and rooms rendered, and the roof reinforced. In Oungoual Bayi, earthworks were performed for water drainage, and the facades were plastered and decorated. Finally, in Agargarn Saka, a house was plastered, and its walls, roofs, doors, and windows were reinforced. Young masons were trained at the various sites. The authorities monitored and accompanied the work, coordinated by the Imane-Atarikh and Iconem teams. The local community participated actively. Craterre-ENSAG provided technical supervision and project framing, with field missions and technical support from the association. Collaboration with local authorities, emphasized at the groundbreaking ceremony, strengthened project support. This collaboration ensures project success and amplifies socio-economic and cultural benefits for the community. In this initial phase, women primarily benefited, strengthening their role in preserving historic houses and transmitting traditional skills. A local journalist ensured visibility by conducting interviews and broadcasting programs on the ALIPH Foundation-funded project. Banners and posters were created to increase public awareness. The association also conducted door-to-door outreach to promote proper conservation and maintenance practices for rehabilitated houses. Geology and environmental science students from the University of Agadez visited the sites to learn conservation and restoration techniques. The president of the municipal council and the sultan of Agadez, represented by a district chief,

(a)

(b)

**Fig. 3.** Orthophotograph of the Great Mosque (c), and images from the video exploring the 3D point cloud [17] (d) ©Iconem.

**Fig. 4.** Visualization before versus after the restoration of a house.

expressed satisfaction and gratitude, highlighting the importance of continuing these efforts to enhance community living conditions and protect heritage.

## 4 Conclusion and Perspectives

The cultural and historical heritage of Niger, rich in archaeological and paleontological sites, constitutes a valuable testament to humanity's creativity and ancient technological innovation. Research in the 1970s underscored the importance of regions like the Ténéré Plain and Termit, while Agadez, with its unique architecture and UNESCO World Heritage status, remains a symbol of the eastern Trans-Saharan trade route. However, this heritage faces significant threats from conflicts in the Sahel and climate change, which compromise traditional ways of life and historical infrastructure. To counter these challenges, concerted efforts in documentation and restoration are underway, notably through 3D digitization led by the Imane-Atarikh association and Iconem, supported by the ALIPH foundation. These initiatives have documented and contributed to the restoration of Agadez's historic center, with targeted campaigns in 2021 and 2024 using traditional techniques. The outcomes, presented in international forums and published in scientific journals, demonstrate the importance and effectiveness of these actions. The project has not only preserved historical structures but also involved and benefited the local community, especially women. Support from local authorities and awareness initiatives, including educational visits for students, have amplified the project's impact. These collective efforts pave the way for the sustainable preservation of Niger's cultural heritage, highlighting the importance of international collaboration and community engagement in safeguarding cultural treasures against contemporary challenges.

Looking ahead, around fifteen houses are yet to be completed soon. Plans include organizing an exhibition on the digitized city in Agadez and Niamey, the multiethnic capital of Niger with a population of 20 million. This initiative could also lead to the use of drones and 3D technology for preserving the impressive ruins of Djado, a fortified city in northeastern Niger [24]. Djado, once a prosperous town, is now abandoned and threatened by the encroaching desert, making its conservation all the more urgent. Virtual tours of the monuments could also be organized from models already acquired with different devices, whether in Niger or for heritage lovers and visitors from around the world because it is essential for the protection of this heritage to make it known to the greatest number of people.

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# Digital Humanities and Physics Applied to the Study of Cultural Heritage Objects: The Case of Ex-votos

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**Abstract.** Several humanities research increasingly assumed the usage of computational technologies in different stages of their work. In this sense, these types of tools could generate theoretical, methodological and institutional issues that should be discussed. The aim of this paper is to present some initial reflections on the use of computer technologies in research in the field of Philology, more precisely with ex-votos (Latin ex-voto suscepto 'the vow/promise made') from the 18th and 19th centuries. Using certain technologies, it is possible to access the deepest layers – those that are not visible to the naked eye – of documentary sources and thus produce a more complete edition that is more faithful to the original. The work of Paixão de Souza [1, 2] is used as a theoretical point of view.

**Keywords:** Ex-votos · Philology · Digital Humanities

## 1 Introduction

Digital Humanities is increasingly gaining strength in the panorama of studies in the Human Sciences. This is no surprise, given that with the development of new technologies, researchers in this major scientific area are looking to apply innovations, especially in the methodological aspects of their research. This is because, as Marquilhas and Hendrickx [3] point out, Digital Humanities has two great virtues: openness (in the senses of accessibility and collaboration) and speed. Thus, there are currently several works that deal in some way with Digital Humanities. In this respect, it's important to realise that the impact of computer technologies is far-reaching. As Fiormonte, Numerico and Tomasi [4, p. 15] point out,

> "[...] the Digital Humanities movement is part of a wider phenomenon, a cataclysm that is changing not only the sciences and their transmission of knowledge, but also [...] the worlds of finance, media, politics, law, commerce and human resources".

About the use of Digital Humanities in the fields of Linguistics (especially historical linguistics) and Philology, we should highlight the work of Paixão de Sousa, who is


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one of the pioneers in this field in Brazil. As a theoretical basis for this work, we will therefore look at some of her texts, such as: Paixão de Sousa [1 e 2].

That said, the main aim of this short text is to reflect, albeit not in depth, on the possible contributions of Digital Humanities in working with the ex-votos that form part of the corpus of our doctoral research. In our (ongoing) research, we have been investigating a rather interesting heritage object. Interesting be-cause, on the one hand, we have an object of religious devotion that constitutes both material and immaterial cultural heritage and, on the other hand, we have a multimodal text created by combining verbal text (the caption) with non-verbal text (the painting) (see Figs. 1 and 2). In addition to their socio-historical background, it is precisely these two major aspects – heritage value and multi-modality – that give ex-votos their unique character.

**Fig. 1.** Ex-voto of Manoel Miguel (1751). [5]

Milagre q̃. Ffes N.o S.o Da Piadade A Manoel
Miguel Laurador Da Erdade Das Cladejras.
Em oLiurar De Hum Prioris E Carttarral De que
Premitta omesmo S.r Seja p.a Sue S.to Seruiço Se
ndo Noanno de 1751


**Fig. 2.** Ex-voto of Ignacio Berrina and Maria Roza (1844). [5]

MILAGRE qVE FES N. S.ra DO CARMO DE EVORA MOMTE
A IGNACIO BERRINA E MARIA ROZA SVA MVLHER
qVE TENDO TRES FILHOS POR DEFERENTES MVLESTAS EM
PERIGO de VIDA PRISIPAL HVM qVE DEITAVA BIXO PELA
BOCA IPEGANDOSE COMFE AMAI DOSDITOS DOENTES N. S.ra
LHE OBRO o MILAGRE EVORA MONTE ANO DE 1844

For now, to define ex voto, we rely on the work of Scarano [6]. According to this author, "[the] Latin locution ex votos means for the grace received in its broad sense. Thus, the intention of the ex-voto (using the scholastic sense of the term) is to pay for something that has been received" [6, p. 36]. It is therefore in the context of a request or a promise that ex-votos arise. There are all kinds of ex-votos – objects, paintings, replicas of body parts in wax, wood or metal. The fact is that any object given as payment for a promise effectively becomes an ex-voto. In this universe of ex-voto possibilities, however, our research will only focus on votive tablets, also known as Brazilian and Portuguese votive paintings from the 18th and 19th centuries. These are small pictures – of varying sizes and shapes – painted with technique, which are offered for a grace that has been obtained.

## 2 Development

In Digital text: a material perspective, Paixão de Sousa takes a new look at the materiality of text in the digital environment: a "disembodied" document. This perspective is somewhat relevant to discussions about Digital Humanities in the field of Philology, as this is an area that constantly uses the material aspects of texts, especially in extralinguistic analyses – linked to Codicology. Therefore, thinking about a disembodied text, according to Paixão de Sousa [1, p. 52], obliges us to.

> "[...] to abandon categories of analysis designed for the analysis of physical objects, both in the documental dimension (this is the case of the "support" category) and in the categories through which we think about the circulation of artefacts, such as the separation between 'production' and 'publication'".

Thus, advances in computer technology have reconfigured the work of re-searchers from different areas with so-called primary sources. Firstly, we should highlight the new possibilities for producing and making available facsimile editions, i.e. the mechanical reproduction of documentary sources. Proof of this is the emergence of various repositories and text banks full of high-resolution photographs, which allow remote access to texts that, in the not so distant past, could only be consulted in situ where they were stored. This access is therefore becoming more widespread, as Quaresma [7, p. 154] points out: "Artificial Intelligence, with its subfield of Natural Language Processing, can play an important role in the analysis and characterisation of historical texts and in their dissemination and widespread access".

With regard to digital access to documentary sources, it's worth highlighting a very important point: if on the one hand we have research that doesn't require physical analysis of the material, because it's interested in the materiality of the texts – support, inks used, etc. – on the other hand, we have research that can only be carried out, given the physical distance from the archives, through sources made available online.

When drawing up our research corpus, we took care to photograph the ex-votos we found with a professional camera and observing some photography techniques. The product we obtained was high-quality images that will later be made available as a by-product of our research. In this way, we will collaborate with the tripod that is very dear to us: preservation, popularisation and research.

Two other tasks that have benefited greatly from advances in computer technology are transcribing and editing texts. The emergence of new software has greatly expanded the capabilities of those who need to transcribe and edit a text (handwritten and/or printed). Optical Character Recognition (OCR) resources, for example, have already been widely used to recognise characters in facsimile editions, thus facilitating the transcription of these texts. An applied example of these resources is the Transkribus platform – a platform for digitisation, recognition, automated transcription and historical research of ancient texts – created by researchers at the University of Innsbruck in Austria.

Another important aspect brought about by these advances was the possibility of associating images (facsimile editions) and transcriptions in an increasingly interactive way. Thus "the hypertext editions also allow simultaneous access to all materials and versions, enabling the reader's view rather than the editor's." [8, p. 125]. This collaborates directly with the process of scientific replicability. In other words, the reader (from the least to the most specialised), when faced with the edition of a document, when comparing image and text, can perceive the interpretations made by the editor and can even propose their own interpretations.

When proposing a digital edition of an old text, it is possible to combine different aspects, or layers, of the same text. In this respect, Lose et al. [9, p. 78] emphasise that.

> "[…] the digital edition, and not merely an edition in digital format, proves to be a completely appropriate type for Philology, which needs to work not only on the text, but also on the paratext, the information that contextualises and gives mean-ing to the edited document. In previous editions, this information came as back-ground information, but in the digital edition this informational framework is fully integrated into the transcribed text, thus creating a perfect harmony between the transcription and all the information that was necessary for the philologist to enter this text and, consequently, perform his function (of bringing the text to life) with more confidence and clarity. The surroundings of the text are always fundamental for a good edition and the digital edition makes this dialogue possible in a natural and sovereign way. Digital editing is complete because the editor can choose the criteria of any type of transcription that already exists and make it dialogue with its paratext through hyperlinks, as well as unfolding abbreviations, corrective movements by the author in the case of a modern text, among other possibilities. What's more, making a text digital means making it easier, more accessible and more widely available".

In the case of ex-votos, a digital edition (or in Banza's words, "hypertext") would make it possible to combine the transcription with various images of these objects. In addition to the multimodal nature of these objects, as they are paint-ings in small frames, the application of physics and chemistry techniques – areas that are somewhat overused in the study of cultural heritage objects – would make it possible to image the objects and characterise them chemically and physically. An example of this type of work was presented by Fachin et. al. [10, p. 95] with a manuscript from Pernambuco from 1826. According to the authors,

> "[…] imaging with different bands of the electromagnetic spectrum and lighting techniques is an initial stage in which it is possible to record relevant aspects of the object as a whole and reveal areas that can potentially be analysed later with other techniques".

The proposal would then be to superimpose on a digital edition of the ex-votos a conservative transcription and a modernised transcription, a photograph with normal lighting, a photograph with shallow lighting, a record with transmit-ted lighting, an ultraviolet fluorescence record, an infrared reflectography record and an x-ray fluorescence record. With all these records, we would create an edition with the various layers (some more visible than others) of the ex-votos we are working with.

To make our proposal a little more tangible, below we present a set of images produced by researcher Márcia Rizzutto of a picture painted by restorer Márcia Rizzo in 2009, created to demonstrate some imaging techniques.

It is noticeable that each technique brings different aspects to analysing the object. At the top of Fig. 4, for example, using infrared reflectography photography, it is possible to access a non-visible layer of the painting, in other words, an underlying image: CADAPAC/M RIZZO RESTAURAÇÕ (our transcription) (Figs. 3 and 5).

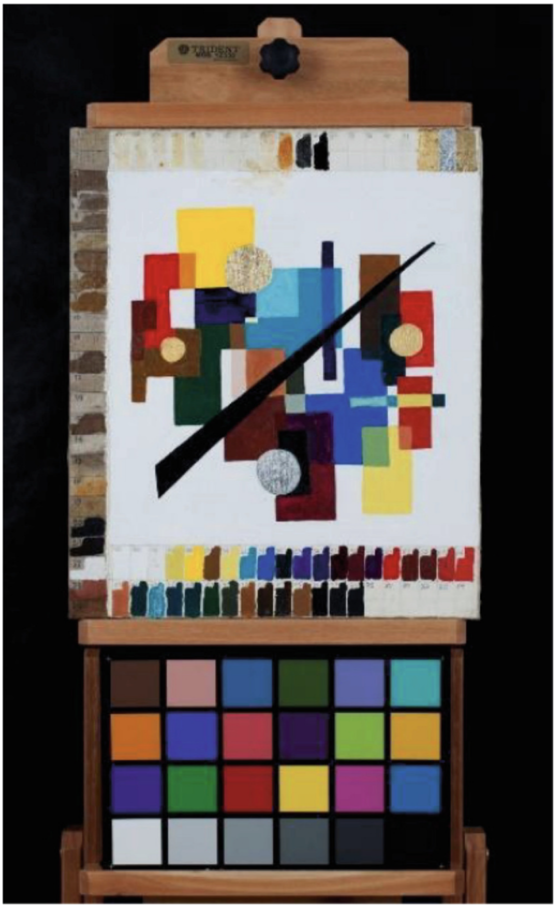

**Fig. 3.** Visible light photography. Source: IFUSP/Jade Zendron.

With the help of Digital Humanities, overlaying and making available the various layers of ex-votos will allow us, in addition to more complete documentation, to understand part of the production process of these objects which, according to Art History researchers [11], are made with little technique. From a philological point of view, this information will help us to better understand the extralinguistic aspects of the ex-votos, which have a direct impact on the intralinguistic and textual aspects.

To carry out this type of editing, it is necessary to carry out various character and text coding tasks. This task is only possible through multidisciplinary work involving philology, linguistics and computing.

Character coding will be indispensable due to the need to include special items in the transcriptions given the varied particularities of each ex-voto (each ex-voto is a text produced in a different place, at a different time and by a different person). It's worth pointing out here that, according to Paixão de Sousa [2, p. 129], "a character on a computer screen is a simulation: it's a visual illusion corresponding to a mathematical code

**Fig. 4.** Photography with tangential light. Source: IFUSP/Jade Zendron

and […] it's something we can't hold in our hands". Thus, we return to the "disembodiment" of digital text, which gives us the possibility of infinite representation. Text coding, on the other hand, is related to the organisation of information in the virtual space of the screen and "[…] can serve the purpose of reproducing as closely as possible a printed or handwritten text on paper, or it can serve to construct new text-objects, free from the simulacrum representation of pages, lines, etc.". [2, p. 129].

In addition to editing the ex-votos, in our research we studied Discursive Traditions as a way of understanding the historicity of these texts [5].

To do this, reliable editions must be taken as a starting point for the subsequent survey and systematisation of Discursive Traditions. At this stage, the use of digital processing and corpora processing tools is essential. This is because when dealing with various data and different variables, the machine helps us to identify recurring traits.

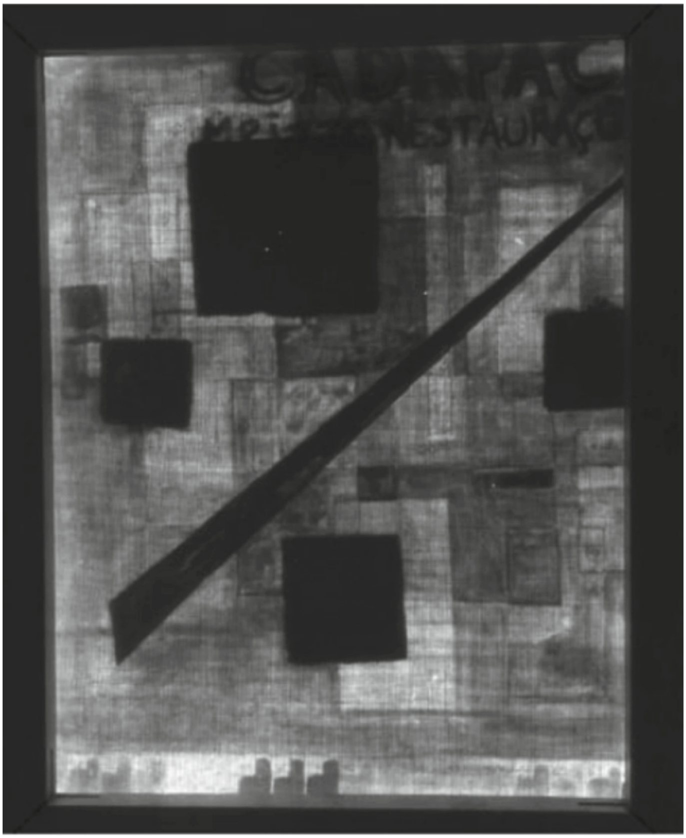

**Fig. 5.** Photography infrared reflectography photography. Source: IFUSP/Jade Zendron

## 3 Final Considerations

In this text, we seek to present some initial reflections produced from our work with painted ex-votos from the 18th and 19th centuries and a possible use of digital tools.

Some people say that machines will replace human beings. We don't agree with that. Technological advances are there to facilitate and automate tasks that were sometimes too costly. Digital Humanities has proven that it is possible to process and analyse a greater amount of data in less time. In this way, research, especially in the fields of philology and historical linguistics, is increasingly able to get closer to the linguistic reality witnessed in documents. The data that reach-es us – as Labov emphasised with the metaphor "[t]he art of making the best use of bad data" [12, p. 20] – is very fragmented. The more data that can be analysed, the better.

Looking at ex-votos from the perspective of Digital Humanities is no different. The most complete possible description of these objects cannot ignore their multimodal nature. Only through Digital Humanities is it possible to describe and give access to the multiple layers (textual and supratextual) that make up these objects which, in their materiality, are so fragile and need to be preserved.

One criticism is the use of so much technology - professional cameras, image processing resources, good word processors, etc. – to ultimately produce a print-ed edition and, when made available online, without any digital interaction.

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**Comments.** The ex-votos presented in this work are part of the corpus of my doctoral thesis. All the material was collected and recorded by me using a semi-professional camera. They were collected through fieldwork at religious sites in Alentejo, Portugal, and in muse-ums in Minas Gerais, Brazil. About the quality of the images, it should be borne in mind that, as the paintings were fixed in different places in museums or churches and could not be removed from their places for recording, there are differences in the photographs caused either by the geographical position of the painting or by the incidence of lighting on the object.

**Disclosure of Interests.** The author has no competing interests to declare that are relevant to the content of this article. A previous version of this text was published in the *Journal (Entre Parênteses)* of the Federal University of Alfenas in 2022.

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# Fostering Community-Cultural Heritage Resilience in Post-disaster Scenarios: Merging Hands-On Experience with Digital Technologies in the OPHERA Project

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**Abstract.** The OPHERA project was initiated in late 2018 by the Regional Secretariat of the Ministry of Cultural Heritage for the Marche Region, following the interruption of emergency activities related to the 2016 and 2017 central Italy earthquakes. As the focus shifted from emergency management to reconstruction planning, OPHERA aimed to spotlight the ongoing cultural heritage restoration in the Marche region and make its artistic, technical, and creative content accessible to a broader audience, not just professionals. In line with the Faro Convention principles, local communities were involved as key stakeholders in this transformative process. The project partnered with several international institutions, including the University of Minho, University of Technology of Cyprus, University of Ljubljana, and University of Ferrara. OPHERA's activities were structured into two phases: a series of workshops to enhance digital heritage and risk prevention skills among 21 cultural operators from eight European countries and the creation of Open-Site events. Held at six selected sites, these events featured workshops, performances, and exhibitions targeting diverse audiences. Despite some challenges, OPHERA successfully fostered community engagement, provided professional growth opportunities, and created a strong sense of shared cultural values.

**Keywords:** Historical Buildings · Preventive Conservation · Post-earthquake Reconstruction · Community Engagement · Audience Development

## 1 Background

Over recent years, a growing number of disasters has affected millions across the world, whether as a result of earthquakes, floods, cyclones, tsunamis or other natural or human-made hazard, including climate change and armed conflicts. In addition to human lives, properties and infrastructure, disasters have caused severe damage to precious cultural heritage resources, as well as the disruption of century-old cultural practices, rituals and expressions.

Experience has shown, in this regard, that the effects of disasters on cultural heritage have a profound impact on the concerned communities, both material and psychological,


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which is further aggravated when populations are displaced. Conversely, the protection of cultural assets and the continuity of cultural practices at times of crisis has shown to be a critical factor of resilience and a condition for lasting recovery. Far from being a secondary aspect, therefore, the protection of cultural heritage from disasters and its rapid recovery and rehabilitation in emergency situations is nowadays recognized as a key humanitarian and security issue, for example within the Sendai Framework for Disaster Risk Reduction 2015–2030 [1], on a par with other major societal concerns (e.g. economic, social, health and environmental).

A stronger consideration for culture and heritage, moreover, goes hand in hand with the need to empower communities, ultimately those who create and transmit such heritage, so as to enable them to play an active role in reducing disaster risks and planning for reconstruction. Again, the Sendai Framework and many other relevant international policies emphasize the importance of placing communities at the heart of disaster prevention, response and recovery. A specific area of work, called "community-based disaster risk reduction" (CBDRR), has stemmed from this approach [2].

Despite the above, local communities around the world are very often not engaged in the protection of their heritage from disasters, nor involved in critical decisions regarding its recovery. In the aftermath of major disasters, while search and rescue operations and stabilization interventions take place, inhabitants of affected areas are typically evacuated and prevented from accessing their houses and cultural landmarks (notably when these are designated as "red zones"). While the safety consideration leading to these measures are understandable, their impact on the affected populations may be considerable. Very often, indeed, this forced separation lasts for months if not years, and sometimes becomes permanent, severing the people from their heritage and reducing their ability to enjoy, participate in, and transmit their culture, with devastating effects on the resilience of communities. In the meantime, priorities and strategies for recovery and reconstruction, with far reaching consequences on the lives of the population, are typically set by governmental agencies, through their staff and "experts", who may or may not be aware of the cultural significance of certain places or practices, and of the new risks affecting them.

In the best scenarios, such as in the recent earthquakes that affected the central region of Italy, the authorities and civil defence agencies work in coordination with cultural institutions, such as the Ministry of Culture, thus enabling the salvaging and conservation of precious assets, made vulnerable by the disaster. Even then, however, and despite the best intentions of all those involved, the focus is too often on the physical recovery and protection of the main monuments and works of art, with less attention paid to the complex web of cultural relationships that binds a community together and with its local built and natural environment, which has been disrupted by the disaster. This may sometimes lead to inappropriate decisions, from the cultural point of view.

An example of such insensitive response to disasters are, in particular as a result of large earthquakes, the new residential areas where evacuees are settled, normally located nearby the damaged historical towns. Very rarely these new urbanized areas offer social and cultural spaces such as squares, cultural centres, museums, libraries which would help to maintain a continuity in the cultural development of the communities. An additional aspect that is often neglected, is the fact that major disasters result often in the creation of new cultural values, either associated with the need to memorialize a tragic event, or simply because of the natural process of social change and transformation that take place after catastrophes, including large reconstruction projects and the relocation of people and their activities. Communities tend to adapt culturally to new circumstances, by attributing new meanings to places and practices, which acquire a special significance to them and in time may become part of their heritage. This ability to adapt is in itself a manifestation of the resilience of communities, while the specialists take, by definition, a more conservative approach and tend to dismiss new ideas and proposals as irrelevant if not dangerous.

The empowering and full engagement of affected populations in the cultural heritage conservation process after a disaster is critical to support their resilience. It may foster a deep local cultural regeneration and would also help specialists in their technical choices and conservation strategies. In the process, local identity values – which are often taken for granted in ordinary times - may be rediscovered and strengthened as a foundation for lasting recovery and sustainable development.

## 2 Introduction

The OPHERA project began in late 2018, following the cessation of emergency activities at the Regional Secretariat of the Ministry of Cultural Heritage for the Marche Region. These activities were initially focused on addressing the aftermath of the earthquakes that severely impacted central Italy in 2016 and 2017 [3].

| | Listed items | Ope-legis items | Total arch. Heritage item | Affected items (damaging assessment required) | affected vs total |
|---|---|---|---|---|---|
| Marche | 3142* | 16250* | 19392 | 2984 | 15% |
| EZ Marche | 1270* | 7582* | 8852* | 2088 | 24% |
| Rest of Marche | 1872* | 8668* | 10540* | 896 | 9% |

Source:
MIBACT SR-MAR - UCCR
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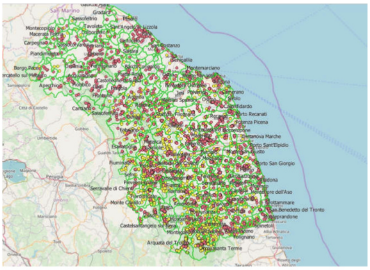

**Fig. 1.** Architectural heritage sites affected by 2016 earthquake in Marche

In the Marche Region, the most affected area, almost 3,000 historically listed buildings (including castles, palaces, and archaeological areas) were damaged or destroyed out of 13,000 protected building (Fig. 1). From these listed buildings, more than 13,000 movable artworks with varying levels of damage were removed and stored in temporary conservation centers. In terms of landscape impact, 285 historic villages were damaged and evacuated. In the Marche Region, more than 348,000 people live in the affected area (22.6% of the total regional population), spread across 85 municipalities, which cover 42% of the entire regional territory. These numbers highlight the significance of the process now beginning in these areas, particularly when comparing the number of historical and artistic sites to the population and the size of the territories involved, revealing a particularly high "density" of cultural heritage (Fig. 2).

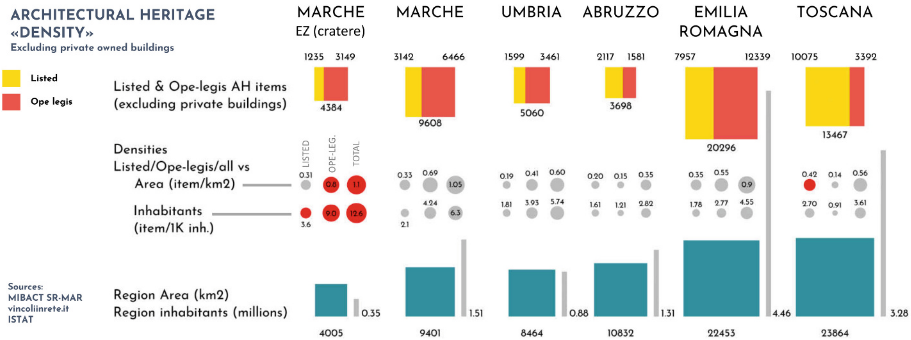


**Fig. 2.** Architectural heritage "density" in the earthquake zone (EZ)

It is likely one of the largest integrated restoration and territorial development processes in all of Europe and represents a unique opportunity to combine the best cultural expertise from across Europe and make it accessible to a broader audience, including citizens, cultural operators, and visitors.

In this scenario, the transition from emergency response to reconstruction planning presented a significant challenge for all involved stakeholders, including local communities, and both local and national authorities. Specifically, the institutions responsible for the protection and enhancement of cultural heritage in the Marche region—one of the areas most heavily affected by the earthquakes—were tasked with overseeing the extensive and gradual restoration and reconstruction of the huge damaged heritage.

This awareness led to the desire to highlight at a European level the ongoing process of cultural heritage reconfiguration in the Marche region. The goal was to make the cultural, artistic, technical, and creative content involved in this process accessible to a broader audience, not just professionals. In alignment with the principles of the Faro Convention, local communities, as the custodians of cultural heritage, were engaged to become key players in a process that will inevitably reshape the historical markers upon which their identity is built. The project partnership was established based on this vision and included the University of Minho (Portugal), the University of Technology of Cyprus, the University of Ljubljana (Slovenia), and the University of Ferrara.

The activities carried out to achieve the goals set were structured in two phases. The first phase provided for a cycle of three workshops dedicated to a team of 21 cultural operators from eight European countries. The workshops, held in Limassol, Cyprus (online, may 2021), Guimaraes, Portugal (july 2021) and Camerino, Italy (September 2021) were aimed at:

- increasing operators' skills on digital heritage and risk prevention, which were deemed strategic for the future of cultural heritage
- co-creating through continuous dialogue with the communities of reference audience development events inside the restoration sites (Cantieri Aperti in Italian, Open

Sites hereof), which are commonly seen as impenetrable places isolated from the surrounding context.

The scientific and cultural background of the project is connected to the theory of restoration developed in Europe over the last two centuries, particularly the theory of "critical restoration" [4] According to this theory, the restoration process involves two key acts: the critical act and the creative act. The critical act involves the cultural assessment of what constitutes art, including the artistic and historical values of an object, and determining what is worth restoring to be passed on to future generations as a legacy. The creative act refers to the additional value introduced by the artist-restorer, who, during the restoration process, may need to enhance or integrate the art object by applying their own creative skills and sensitivity. Consequently, the theory of restoration concludes that "art restoration is an art form in itself." Paradoxically, even the decision to refrain from additional interventions on the art object (i.e., preserving it as a ruin)—a concept known as "Romantic restoration" theorized by J. Ruskin and W. Morris [5]—represents a creative choice. This choice is based on a case-by-case critical analysis that guides the art restorer in recognizing the artistic and historical values of the object in its current state. Therefore, the restoration process can be considered a form of art creation, especially in post-disaster scenarios where the creative and technical aspects of cultural heritage restoration are intensely challenged. The OPHERA project's objectives were directly linked to the recognition of this creative experience. First, it aimed to broaden and diversify the audience for this form of art. Second, it sought to provide cultural operators involved in managing such scenarios with the fundamental knowledge needed to assess and enhance cultural heritage during the restoration process. These two goals were combined through international exchange.

## 3 Project Strategies: People, Cultural Heritage, Technology Innovation

The OPHERA project is based on a combination of strategies that aim to put people, cultural heritage, and technological innovation at the center (Fig. 3):

- Audience development.
- Capacity building.
- Transnational mobility.
- Communication and dissemination.

### 3.1 Audience Development

The project aimed to enhance the audience development [10] for the cultural and artistic aspects of the cultural heritage restoration process through three main directions:

- Expand the current audience: engage the existing network of cultural operators and artists working in the field of cultural heritage restoration at various levels.
- Diversify the audience: attract individuals from different demographics beyond the current audience, including local residents, visitors, senior citizens, children, and young people.

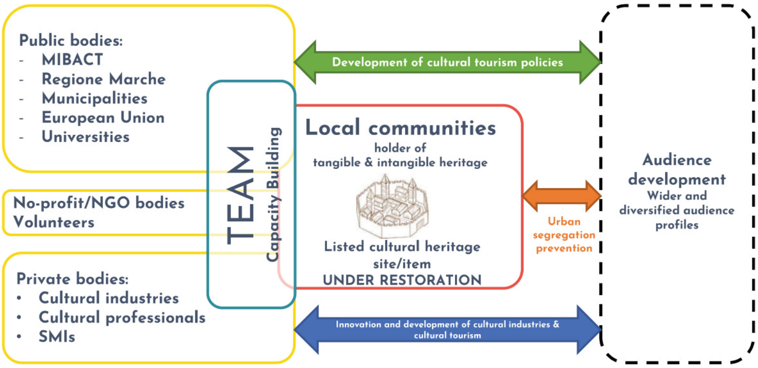


**Fig. 3.** OPHERA project strategy

- Strengthen relationships: deepen the engagement with both the current and new audiences.

A graphic representation of the OPHERA audience development strategy is represented below (Fig. 4):

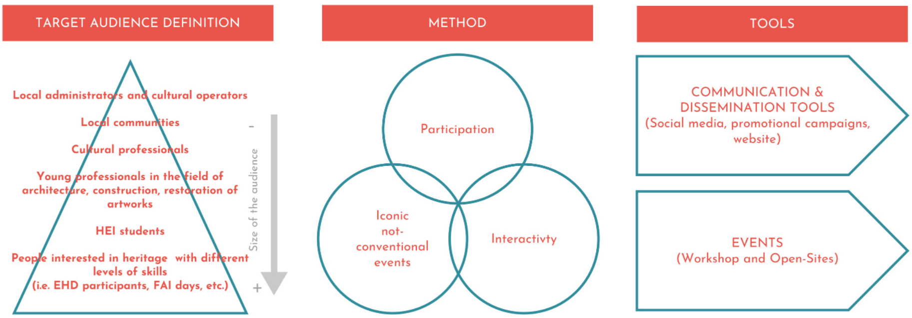


**Fig. 4.** OPHERA project audience development strategy

Normally, only the art and cultural professionals involved in the restoration process had access to the cultural contents linked to the reconstruction activities of the territories affected by the 2016 Central Italy earthquake. This audience group included local cultural managers, architectural restorers, artwork restorers (paintings, sculptures, ancient books, archives, church fixtures and mobile furniture, etc.), restoration technicians, specialized restoration company operators, cultural heritage academics, local administrators, staff of local public institutions, and representatives of local cultural foundations and associations.

The project strategy aimed to widen the current audience to include the Italian and European community of cultural operators through its main activities:

- Training Activities: these have to be dedicated not only to Italian but also to European cultural operators, who would have the opportunity to attend open-days as experts.

- Open-Days and virtual reality experiences: Thanks to the communication campaign, these events would attract cultural operators from Italy and Europe. This new group of cultural operators would benefit from high-level art and cultural content to enhance their knowledge. At the same time, they would be encouraged to share their experiences and skills with site restoration operators, creating opportunities for collaboration and contributing to ongoing "cultural creation".
- Dissemination campaign: Conducted through the website and social media, this campaign would reach cultural operators worldwide. Many cultural operators active in the same field would follow the project activities online and express their interest by joining the community through the website.

With reference to the audience diversification, it is necessary to note that the cultural offer of the territories affected by the 2016 Central Italy earthquake was quite poor, as the majority of the sites dedicated to cultural events were not usable. The local communities settled in those territories were therefore a key profile of the project's audience development strategies. Although this group of people lived near the place where art and cultural contents were created thanks an extensive restoration process, they represented a "non-audience" since there were no tools and opportunities for them to access the cultural heritage restoration art and cultural contents. Through the training of a team of cultural operators, the project aimed to create the foundational conditions for the initiation of a new level of cultural events in that area. Indeed, the project aimed to concretely demonstrate that cultural values could be expressed with new tools and that activities such as restoration held significant cultural and creative content, bringing universal values to be shared.

Through the Open Days, the OPHERA Project concretely hosted cultural events designed for a new audience. Participants had the opportunity to engage, acquire new cultural knowledge, and meet the key figures involved in the restoration process in their area. The Open Days and the digital interactive exhibition were designed to involve visitors in the decision-making process of restoration and to raise awareness about the complexities of day-to-day restoration work. This aimed to address public concerns about the lengthy duration required for the restoration and reconstruction of their towns' physical identity. Moreover, during the Open Days, the audience attended in-person meetings and workshops with restoration professionals and had the chance to provide feedback and suggestions to align reconstruction efforts with community aspirations.

The strategy for diversifying audience profiles through the engagement of new publics also included traditional visitors [7]. The areas affected by the 2016 Central Italy earthquake were relatively close to major tourist cities that attracted many Italian and international visitors. Consequently, the communication campaign for the Open Days targeted these areas to draw both Italian and international visitors to the restoration sites where the Open Days and exhibitions were held. Table 1 shows the distances and travel times by car between some key tourist locations and the main restoration sites (Castelsantangelo sul Nera, Arquata del Tronto).

Young people and children were also an essential part of the audience development strategy. The project leader established agreements with primary and secondary schools at the national level to encourage their participation in the Open Days. Specifically,

**Table 1.** Distances/travel time between project 'sites and tourist locations

| City | Main tourism typology | Castelsantangelo sul Nera | Arquata del Tronto |
|---|---|---|---|
| Rome | Cultural/religious | 180 km/2 h 30 min | 156 km/2 h 20 min |
| Perugia | Cultural/religious | 100 km/1 h 30 min | 136 km 2 h 20 min |
| Assisi | Cultural/religious | 83 km/1 h 12 min | 119 km/2 h 6 min |
| Norcia | Cultural/religious | 45 km/50 min | 47 km/1 h 9 min |

students from schools in the earthquake-affected areas were asked to create artworks (physical or digital) depicting how they envisioned the restoration of cultural heritage.

These works were exhibited during the Open Days and presented by the students to visitors. Specific activities dedicated to young people and children were organized during the Open Days. Strengthening the relationship with current and new audience profiles was a key objective of the interactive content prepared for the Open Days, including 3D virtual environments, as well as the open laboratories. The goal of the project was to make the complex cultural content of the restoration process accessible through intuitive and interactive tools that allowed people to feel like active participants in the reconstruction process. The digital content and tools aimed to support this sense of involvement [8]. Additionally, sharing the achievements of the restoration process on social networks, along with other actions outlined in the social media strategy (see communication campaign description), helped foster a sense of belonging among visitors, leaving a lasting impression on their memory and heart [9].

### 3.2 Capacity Building – Training and Education

Capacity building—training and education—was identified as a prerequisite for achieving audience development. The project strategies to address capacity building in the field of training &education were as follows:

- To increase the skills of restoration professionals in the areas required to perform audience development activities (digital methods and tools for cultural knowledge communication and visualization, methods and tools for the preventive conservation of cultural heritage);
- To organize project activities in a manner that facilitated constant collaboration between cultural operators from different European cultural institutions;
- To combine traditional training methods with fieldwork and practical activities through the organization of cultural events, in order to enhance the operational capacity of the training participants.

According to the above strategies, the general criteria for workshop organization and participant selection were as follows:

- Participants were selected during the project preparation to attend the three workshops, short internships, and Open Days.
- Based on the available budget, it was possible to train 20 cultural operators, who received participation grants to cover part of their travel and accommodation costs.

- Applicants were required to be art/cultural operators or graduates in art disciplines, active in the Creative Europe programme eligible countries [10].
- Priority was given to applicants active in cultural institutions located in territories affected by earthquakes and other natural disasters.
- The maximum number of participants active in Italian cultural institutions was 14.

The initial two workshops offered participants a comprehensive introduction to the pertinent fields, presenting a clear picture of the current state-of-the-art methods and technologies. These workshops specifically focused on digital technologies for understanding and disseminating cultural heritage values, as well as strategies for preventing risks and mitigating damage to cultural heritage. The third workshop, along with the subsequent field activities for the preparation of the Open Days, engaged the trained cultural operators in the actual design and execution of a cultural event based on the topics covered in the first two workshops. This was done to prepare them to promote similar activities at other restoration sites during the long-term post-earthquake reconstruction process, potentially through collaborations with European institutions involved in the project execution.

Additionally, since many of the cultural operators involved were under 35, they may gain professional and cultural experience that would enhance their employability once the reconstruction process was completed.

### 3.3 Transnational Mobility

Transnational mobility also complemented the previous strategies in order to:

- Envisage the participation of cultural operators from different European countries in all project activities.
- Foster the participation of European cultural operators through the web and social media.

The pandemic significantly affected the ability of non-Italian partners to carry out the planned field activities. The situation was further complicated by the varying levels of virus spread (and consequently different restriction measures) among the four EU countries involved in the project, as well as by the policies adopted by their respective institutions. The project activities were fully implemented despite the challenges posed by the pandemic.

### 3.4 Communication and Dissemination

The communication strategy utilized different means of communication tailored to the target audience, which was segmented geographically and by familiarity with the Project's reference sectors (e.g., cultural heritage, restoration, painting, architecture). Given the nature of the scheduled events, specific communication channels were identified for each target group. It was assumed that a higher degree of specialization would correlate with greater interest in the project, regardless of geographical distance from where the activities were held. Conversely, it was assumed that audiences less familiar with the Project's cultural content would be more attentive to initiatives proposed in proximity to their geographical location and familiar places, based on their social habits. This method enabled the identification of suitable communication channels for different target groups and their geographical areas.

## 4 Output and Outcomes

### 4.1 Output

The Project's expected outputs have been fully achieved, despite several unforeseen events that occurred during the implementation phase, particularly the outbreak of the pandemic in February 2020, just before the start of the workshop cycle [11]. Thanks to the spirit of collaboration among all the partners and the support of the Project Officer, the Project was revised by postponing the workshop cycle by one year. This allowed for all scheduled activities to be maintained, with additional functional activities added to retain the selected cultural operators. The three workshops were successfully carried out, as evidenced by the strong support and positive feedback received from all participants. It is worth noting that only one out of the three workshops was held remotely, while the other two were conducted on-site. Partners and participants contributed to the site opening events, preparing the content and design of the events while taking into account the new safety requirements due to the pandemic. The six site opening events featured numerous initiatives and elicited a strong response from the target communities, particularly local communities, young people, and the elderly. These events also had a significant media impact at both national and European levels, which continues to produce positive outcomes even after the activities have concluded.

The Project execution have produced the following outputs, which are detailed in Table 2:

- 6 conservation sites open to visitors
- 16 activities co-created by the local communities and the cultural operator teams addressed to new audiences such as laboratories, photo contests, exhibitions, music concerts, etc.
- 8 professional audiovisual works edited
- 22 cultural professional joined the 3 international workshop
- 4 webinars organized during the lockdown period
- 4 films produced by the participants through the OPHERA Talks
- 2 scientific papers
- More than 30 local, national and European institutions engaged in the project

**Table 2.** OPHERA project detailed output

| Name of work, service or artist | Type of works or services |
|---|---|
| Paper in Revista PH Instituto Andaluz del Patrimonio Histórico (IAPH) | Newspapers/journals/periodicals |
| Paper on Art Tribune "Marche dopo il terremoto del 2016. A che punto siamo?" | Newspapers/journals/periodicals |
| Paper on Art Tribune website March 2022 | Newspapers/journals/periodicals |
| OPHERA workshop Camerino | Conferences, laboratories, seminars, forums, workshops and associated events |
| OPHERA workshop Guimaraes | Conferences, laboratories, seminars, forums, workshops and associated events |
| OPHERA workshop Limassol - online | Conferences, laboratories, seminars, forums, workshops and associated events |
| Cantieri Aperti video launch | Audiovisual works (films, multimedia, videos, video games) |
| Collegiata Santa Maria di Visso - Structural monitoring campaign for seismic risk prevention | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Ascoli Piceno - Palazzo Saladini Pilastri | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Acquasanta Terme - Castel di Luco | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Monte San Martino | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Pieve Torina - Complesso Sant'Agostino | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Visso - Chiesa Collegiata S. Maria | Audiovisual works (films, multimedia, videos, video games) |
| Short-movie Visso - Palazzo dei Priori | Audiovisual works (films, multimedia, videos, video games) |
| Transform by Listening - Acquasanta Terme | Conferences, laboratories, seminars, forums, workshops and associated events |
| Matter & Voids - Acquasanta Terme | Conferences, laboratories, seminars, forums, workshops and associated events |
| Approaching the travertine - Acquasanta Terme | Conferences, laboratories, seminars, forums, workshops and associated events |
| Talking stones - Acqusanta Terme | Exhibitions |
| Memories from the drawers - Acquasanta Terme | Exhibitions |

(*continued*)

**Table 2.** (*continued*)

| Name of work, service or artist | Type of works or services |
|---|---|
| Voices of the worksites - Acquasanta Terme | Other |
| The restoration on display - Acquasanta Terme | Exhibitions |
| Notes of restoration - Ascoli Piceno | Musical works and concerts |
| The restoration on display - Ascoli Piceno | Exhibitions |
| Hands at works - Visso | Conferences, laboratories, seminars, forums, workshops and associated events |
| Voices of the worksites - Visso | Other |
| The restoration on display - Visso | Exhibitions |
| Sharing the rebirth - Photo Challenge & online exhibition | Other |
| Memoria - urban photo exhibition - Monte San Martino | Exhibitions |
| Voices of the worksites - Pieve Torina | Other |
| The restoration on display - Pieve Torina | Exhibitions |

The above outputs (creative works and services) are available in the project website (www.ophera.beniculturali.it) and in the OPHERA social media [12– 14].

Thanks to highly competent partners, the Project focused on the use of digital technologies applied to cultural heritage to facilitate the understanding of the artistic and cultural contents inherent in the restoration process by a wider and more diversified public. The following technologies were applied:

- Survey and digital rendering of cultural heritage through 3D laser scanners and drones for digital photogrammetry [15]. These technologies enabled interactive and immersive 3D modelling and therefore, during the activities performed in the six restoration sites, they facilitated the understanding of the contents by users, in particular the general public and children.
- Digital photography and social media communication were used during the 'Sharing the Rebirth' initiative, where primary and secondary school students had first to reproduce and reinterpret photo subjects in the old town of Monte San Martino and then they had to post them on the Project's social media and get users' feedback. In this case, therefore, technologies were used to make the Project's activities for children more attractive, intuitive and interactive.
- Definition and installation of a triaxial digital monitoring system at the Collegiate Church of Visso by the partner University of Minho [16]. In this case, real-time data and interpretation methods were disclosed during the event held in Visso in order to make the users more directly involved in heritage management the importance of risk prevention.

### 4.2 Outcomes

The cycle of workshops and the open-site events engaged many professionals from the restoration sector, including artists, technicians, and local administrators, who deepened their understanding of the cultural, artistic, and creative aspects of cultural heritage restoration. Cultural operators who typically work in the project's target sectors were selected to participate. They explored the challenges linked to the restoration process in Central Italy, which began after the earthquakes of 2016 and 2017. Conversely, during the Cantieri Aperti (open-site) events, agreements were made with professional associations of engineers, architects, and restorers, significantly expanding the audience of professionals specializing in the field. As shown by the professional profiles in the booking system tracking system and the satisfaction questionnaires, the response to these events was very positive, with over 40% of participants coming from the project's target sectors [17].

New audiences gained access to the cultural content inherent in the restoration process not only through the highly successful open-site events but also through the online activities developed during the COVID period (such as OPHERA talks, OPHERA webinars, etc.). A key factor in this success was the varied nature of the open-site events, which made it possible to engage different target audiences with specific interests (e.g., gaming, music, art, food, etc.).

These new audiences were involved and had access to the cultural content of the ongoing restoration process, particularly thanks to specific activities formulated by the project team, which included staff from partner organizations and cultural operators trained during the three workshops. The main target communities were the elderly, young people, children, and people with disabilities. Young people, in particular, were involved in targeted activities such as the restoration workshops held in Visso, in partnership with the Istituto Centrale per il Restauro (the Italian Central Institute for Restoration) (Fig. 5). All sites featured the multimedia exhibition based on digital 3d model of cultural heritage called "Il restauro in mostra" (Restoration on Show), where visitors could explore the most significant and challenging aspects of the restoration choices made through intuitive panels and videos, facilitating effective knowledge transfer.

**Fig. 5.** Open worksite event in Visso "il restauro in mostra"

Young people played an active role in “Note di restauro” (Restoration Notes), an event where students from the Ascoli Piceno music school performed Baroque music, alternating with storytelling by the restoration team in the Hall of Mirrors of Palazzo Saladini in Ascoli Piceno (Fig. 6). The audience was primarily composed of young professionals, partly due to a special collaboration with the Italian Association of Architects. For children, a special initiative called “Sharing the Rebirth” was conducted in the open site of Monte San Martino.


**Fig. 6.** Open worksite event in Ascoli Piceno “Note di restauro”

It was a photo contest for students aged 9–14, where they were tasked with recreating photos of historic places in the old town of Monte San Martino, engaging residents, visitors, and tourists on the topic of social rebirth linked to urban recovery after an earthquake. The photos were then posted on the project’s Facebook page. This initiative involved over twenty pupils aged 9–14 and had a strong external impact, receiving great feedback and appreciation from nearly 1,000 social media users regarding the pictures posted on the project’s social networks. As part of the open site at Castel di Luco in Acquasanta Terme, workshops were held to rediscover the techniques for processing travertine, a typical stone of the area. These workshops were aimed at children and the visually impaired, involving two local non-profit organizations specializing in these activities. These events were also well-received, as evidenced by the positive feedback in the satisfaction questionnaires completed by visitors. The elderly were engaged through initiatives such as visiting restoration sites where cultural heritage assets were closed to the public due to ongoing restoration works. In these activities, the over-50 age group often represented about 50% of visitors, typically with medium to low levels of education. This high level of engagement indicates that the most deeply rooted locals have a strong desire for the restoration of places they have always identified with. Public spaces like squares and cathedrals, which are currently closed due to earthquake damage, are vital markers of these people’s lives. Responding to this “need for memories,” initiatives called “Voci di cantiere” (Voices from the Site) were organized at the restoration sites (Figs. 7 and 8).

These events not only allowed visitors to access the sites but also provided insights from restorers on the most significant aspects of their interventions. Topics included decisions about demolishing unstable parts, reconstructing lost elements, employing

**Fig. 7.** Open worksite event in Castel di Luco "voci di cantiere"


**Fig. 8.** Open worksite event in Visso "voci di cantiere"

methods and techniques for seismic prevention, and addressing the vulnerability of historic buildings due to construction errors or later modifications. The "Voci di cantiere" initiative also highlighted the voices of young professionals, who were well-received by audiences for their passion and communication skills, as evidenced by the satisfaction questionnaires. The relationship between existing and new audiences was deepened and strengthened, thanks in part to the co-participation of these groups in the events. Especially during Workshop 3 and the open-site events, these groups interacted and raised awareness about the importance of community involvement in the restoration process, particularly in the context of post-natural disaster restoration, which often operates on medium- to long-term timelines. The capacity building strategy was addressed by providing a number of workshops including training and skills development activities through hands-on practice sessions and teamwork.

The first workshop, 'Digital technologies for knowledge and promotion of cultural heritage during the restoration & reconstruction process', was held online live from 17 to 21 May 2021, as, due to COVID-19 restrictions in place in the country concerned, the partner Cyprus was not allowed to organise an in-person workshop. This workshop was aimed at providing participants with an overview of the most advanced knowledge in the field of digital technologies applied to the knowledge and promotion of cultural heritage, in particular in post-emergency phases where restoration works are being carried out. Although this online workshop did not allow the on-field activities that had been scheduled to be performed, it actively engaged all participants (Fig. 9).

**Fig. 9.** Workshop 1 during one of the keynote lectures

Participants were asked to develop an intervention strategy for a site under restoration they knew, critically using the knowledge gained from the interventions scheduled in the sessions of 18,19 and 20 May 2002, and then share it with all the participants in the final session of 21 May 2021. The workshop was structured as follows:

- PHASE I - DAY 1: the project was introduced and presented, and the topics ‘Lessons Learned from the Recent Earthquakes in Croatia and Resilience of Cultural Heritage Assets’ and ‘Understanding Complexity and Quality in 3D Digitization of Tangible Cultural Heritage’ were analyzed with guest speakers. A round table of the Presidents of ICOMOS International, ICOMOS Italy, ICOMOS Slovenia and ICOMOS Cyprus was held.
- PHASE II - DAYS 2, 3 and 4: several speeches were delivered by researchers, entrepreneurs and international experts in the field of digital heritage, with a special focus on the application of these technologies in emergency phases. The fifteen speeches delivered covered both general and methodological topics, as well as case studies and successful stories. The most interesting speeches include ‘The Arches Open Source Software Platform: Heritage Management Use Cases’, by David Myers from the Getty Conservation Institute, USA, and ‘Digital Technologies for Informed Conservation of Cultural Heritage: Diverse Pragmatic Examples’, by Rand Eppich - Heritage Development, Spain.
- PHASE III: The last day of the workshop focused on the proposals for implementation strategies prepared by the participants. Each participant developed a strategy, based on their own experiences and drawing insights from the presentations given on the previous days. Proposals were shared and discussed with the other participants, staff and guests, focusing on critical issues and strengths.

The Cyprus workshop received significant positive feedback from all participants. Through some evaluation questionnaires they appreciated the fact that the workshop "gave the possibility to fruitfully interact with participants having a different professional background" (85%), and for all participants "the knowledge acquired during the workshop will be helpful for personal and professional development during and after the project lifetime".

The second workshop entitled 'Traditional and Innovative Methods for Structural Monitoring and Safety Assessment of Built Cultural Heritage' was held in presence from 28 June to 1 July 2021 in Guimaraes, Portugal. This workshop was attended by 13 participants from five European countries. It aimed to develop expertise in the prevention of damage to cultural heritage from natural disasters, using various methods and tools, including innovative ones that are now available. The University of Minho serves as a benchmark for this research at an international level. The workshop was organized into four parts:

- The first one focused on the report 'Cultural Heritage & Earthquakes', where experts from the Portuguese staff and invited guests engaged the participants on the topic of cultural heritage transformations in earthquake-prone areas, risk management methods and conservation best practices for historical and artistic heritage subject to seismic risk. At the beginning of the workshop, the working theme of the workshop groups was proposed. Groups were asked to design a system at a preliminary level for monitoring a cultural asset of their choice.
- The second phase of the workshop focused on 'Structural Monitoring', also providing practical training on the use of digital triaxial accelerometers by the participants.
- The third part focused on conservation. Experts shared their presentations on 'Preventive conservation and management of cultural heritage with support on BIM' and talked out the challenges of the relationship between conservation and communities. Also in this phase the participants worked in groups and carried out practical activities, with 'exercises on the analysis and interpretation of monitoring data'.
- The fourth phase took place in the field, looking at the monitoring system of the Ducal Palace in Guimaraes (Fig. 10). This phase ended with the presentations of the projects developed by the groups of participants during the previous phase.

The Guimaraes workshop lasted less than planned due to COVID-19. The organizers had to take into account all the restrictions and measures in place both in the host country and in the countries of origin of the participants. As a consequence, it was a burdensome task to organize this workshop. In addition to technical-scientific contents, the workshop held in Guimaraes also had a strong impact on the "intangible" construction of a team of cultural operators, who finally had the opportunity to get to know each other and work together on site. The feedback from the evaluation questionnaires testifies to the above. The opportunity for interaction with other participants and Project staff was appreciated (100%) and the importance of the knowledge gained for one's own career path was acknowledged by the majority of participants (>80%).

The third workshop was held from September 6 to 10 in Camerino, Italy. Camerino is a symbolic location for the OPHERA Project, as it was one of the areas most severely affected by the 2016 earthquakes in Central Italy. In fact, the entire medieval historic center was almost completely inaccessible to citizens until a few months ago. The aim

**Fig. 10.** Workshop 2 – site visit at Ducal Palace in Guimaraes

of the workshop, entitled 'Opening the Earthquake-Damaged Cultural Heritage Conservation Process to Communities: Methods and Tools,' was to co-design the Open-Site events for the opening of restoration sites in the target area. A few months before the workshop, the project 'staff initiated discussions with public and private entities to gather applications for restoration sites to join the OPHERA Project's Open-Site events. After various consultations held remotely, the workshop participants selected six sites that effectively represent the artistic and cultural heritage of the earthquake-affected territory. The restoration work carried out after the 2016 earthquake in Central Italy involved a considerable number of cultural heritage properties. The Project selected six properties to be made accessible to the public through the Open-Site events, representing the most significant architectural types in the area (Fig. 11):

- The church-cathedral (the Collegiate in Visso), the cornerstone of urban development.
- The church-convent of mendicant orders (the St. Augustine Complex in Pieve Torina).
- Gothic civil architecture (Palazzo dei Priori in Visso).
- The urban noble palace (Palazzo Saladini di Rovetino in Ascoli Piceno).
- The medieval castle (Castel di Luco in Acquasanta Terme).
- The medieval historic conurbation on the hilltops (Monte San Martino).

The third workshop began with a ceremony that included speeches from several authorities, including a welcome address by Ms. Alessandra Luchetti from EACEA, and a presentation by the special administrator (Subcommissario Governativo) for post-earthquake reconstruction, who provided an overview of the progress in restoring the cultural heritage damaged by the 2016 earthquake. Later in the afternoon, the Project Coordinators presented the workshop's objectives, outlined the characteristics of the six sites, and specified the deliverables expected from the six working groups—one for each site—by the end of the workshop. The second day focused on knowledge exchange and sharing similar experiences with national and international experts, emphasizing audience development and community involvement. Contributions included insights from the Fitzcarraldo Foundation on audience development and a presentation by Antonio Massena on the 'Recovery and Reuse of Cultural and Architectural Heritage Damaged


**Fig. 11.** Open worksite events locations

by the Earthquake,' among others. These artistic and cultural projects aim at revitalizing the urban and social fabric. On the third day, the 21 participants from eight European countries visited the six Open Sites in groups (Fig. 12). Meetings and feedback collection activities were organized in advance. Feedback was gathered from the target communities identified by the Project, as well as from reconstruction stakeholders such as architects, engineers, local administrators, property owners, and investors. On the fourth and fifth days, the groups designed the open-sites events using a template and materials provided by the organizers. They were tasked with outlining events for each site, prioritizing target audiences, and making an advanced proposal that included an economic framework to ensure the available budget could accommodate each event. Each group, in addition to cultural operators, included staff members and other external figures to enhance interaction and make the sessions more dynamic and engaging. On the afternoon of September 10, 2021, each group presented its proposal for a site opening event during a plenary session. For each proposal, the groups and staff engaged in a thorough discussion to gather feedback, which was crucial in making the initiatives as compatible and sustainable as possible. The lectures, plenary sessions, and other parts of the workshop were broadcast live on the Project's Facebook page and are still available for viewing. Feedback from participants of Workshop 3 showed strong involvement and appreciation for both the content and the organizational arrangements. About 89% of participants acknowledged the "opportunity to fruitfully interact with participants from different professional backgrounds," and all participants reported being "satisfied with the knowledge gained throughout the workshop". It is worth noting that the workshop held in Camerino was strongly and emotionally impactful for all participants, who spent time together even after the workshop activities had concluded. This strong spirit of collaboration greatly contributed to the excellent outputs presented by all participants.

Of course the strategy of the transnational mobility has been partially impacted by the COVID restrictions and for this reason it was not fully addressed as planned in the project proposal. The mobility planned in connection with the holding of Workshop 1 in Limassol, Cyprus, was not fully implemented, as the restrictions on air travel still in place in May 2021 meant that the workshop had to be held remotely, via the ZOOM platform.

**Fig. 12.** Workshop 3 in Camerino (Italy). Field activities in the restoration sites.

However, thanks both to the online meetings held before and during the workshop, and the subsequent physical meeting events of the participants in Guimaraes for Workshop 2 and in Camerino for Workshop 3, international mobility was kept at the heart of the project's priorities. The call for workshop participants had an excellent international response, demonstrated by the numerous applications (over 120) received from around 15 European countries. The team of young cultural professionals was chosen by an independent commission set up by the Project Coordinator and selected a heterogeneous group of experts in terms of both skills and geographical origin. Due to the success of the call, the available places were expanded. Initially 20 participants were expected, which was increased to 22. The main information about participants is given below:

- Nationality: 8 (Italy, Portugal, Spain, Cyprus, Slovenia, United Kingdom, Denmark, The Netherlands)
- Participants' professions:

  - Cultural heritage restorers. Curators of events and exhibitions
  - Cultural workers and employees
  - Students, researchers, and academics
  - Officials and administrators of public and church bodies
  - Local and national administrators
  - Professionals and entrepreneurs in the fields of art and creativity

In addition to the participants, speakers at the three workshops came from various European countries, Taiwan and the United States, which further increased the international character of the project.

Table 3 represents the number of participants involved in the project which worked in any other country than their own country of residence. In the below quantities are not included the partner staff.

The mobility of project staff was added to that of participants. This was actually already quite limited in the project proposal as the idea was to allocate as many resources

**Table 3.** OPHERA project participants international mobility

| Country of origin | Number of mobile cultural and creative professionals (total) | Number of mobile cultural and creative professionals (women) | Number of artists or creators (total) | Number of artists or creators (women) | Number of mobility days (total) |
|---|---|---|---|---|---|
| Italy | 8 | 4 | 2 | 2 | 28 |
| Denmark | 1 | 1 | 0 | 0 | 9 |
| Spain | 1 | 1 | 1 | 1 | 20 |
| Cyprus | 0 | 0 | 1 | 0 | 5 |
| Slovenia | 2 | 1 | 0 | 0 | 9 |
| Portugal | 2 | 1 | 0 | 0 | 12 |
| Netherlands | 1 | 1 | 0 | 0 | 9 |
| | **15** | **9** | **4** | **3** | **92** |

as possible to implement activities and support participants through lump-sum grants. Totally 19 staff members were engaged in mobility actions, for a total of 60 days mobility days.

The quantitative and qualitative assessment of the results allowed to determine several impacts produced by the project activities, specifically:

- Engagement of local and regional institutions cultural operators in the open-sites events organization;
- Increase of international outlook of local cultural operators;
- Enhancement of audience knowledge about art creation during the post-earthquake restoration process;
- Increased community awareness of the complexity of restoration practices, particularly in post-emergency scenarios.
- Enhancement of audience awareness about the importance of preventive conservation;
- Enhancement of partners' skills in audience development activities
- Increase of participants' skills in workshops on the topics proposed by the project
- Increase of partners' skills in project management within the Creative Europe programme

Regarding the promotion, communication, and dissemination strategy, the project achieved a very satisfactory level. The pandemic necessitated a restructuring of the communication approach. In addition to the traditional forms of communication and dissemination, methods were adopted to maintain contact between participating professionals through web platforms. This ensured continuity with the project's proposals and objectives. In general, various communication contexts were prioritized, choosing local, national, and European communication channels, including the use of trade press, professional web portals, and social media. At least 65,000 users were reached, with 26,000 through the website and about 2,200 through social media. More than 700 users were engaged through public relations, of which 250 were cultural and creative professionals. A strategy for involving partners was also developed, which included a schedule of periodic meetings and the ability to share materials via a dedicated platform. Content was shared uniformly across the Facebook page, Instagram, and YouTube, allowing partners to further disseminate the proposed initiatives.

The communication plan applied to the project also strengthened direct relationships with local municipal administrations, involving them not only in technical and administrative aspects but also in participatory roles. Local administrators, technicians, and professionals were directly involved in the process of disseminating and creating content (e.g., audio-video, interviews, conferences, workshops, guided tours), setting the stage for the implementation of the Cantieri Aperti events, the final part of the project. During these events, the professionals involved, the project team, and the partners met the public and local communities directly at the restoration sites, which were specially opened for these events. Thanks to the communication plan, the overall impact of the communication and dissemination strategies was significant, both on the Project, the partners involved, the creative sector, and in relation to the priorities set within the framework of the Creative Europe program. For example, to promote Cantieri Aperti events among local communities, commercials on local and/or national TV channels were used. To reach restoration specialists across Europe, investments were made in promoting these open sites through specialized web platforms. The results confirm the soundness of these strategic choices for two reasons:

- the high level of participation in activities targeting general audiences, such as Voci di Cantiere within the Cantieri Aperti framework;
- the positive feedback from specialized target audiences for activities directed towards them, such as the call for participation in the workshop cycle, which was posted on the aforementioned platforms and received over 100 applications from more than 15 European countries.

The impact of communication and dissemination strategies on partners was significant, as evidenced by the numerous information requests received by cultural operators in the European countries where the partners are based, namely Italy, Cyprus, Portugal, and Slovenia. There were also numerous requests to present the Project in contexts beyond those of the partners, such as conferences, magazines, journals, and publications.

## 5 Final Remarks

As stated above, even if the impact of the pandemic on the project was significant, it was possible to implement the project and achieve the expected results, even exceeding initial expectations. There are numerous positive stories and events that occurred during the project. Among the most significant are the following:

- The group of cultural workers who participated in the workshops quickly established a positive and collaborative atmosphere with the project staff. Many participants expressed a desire for the project and its activities to become somewhat “permanent,” as they enhance and give new impetus to the professional activities that each of them normally performs.

- The interaction between the working group, consisting of staff and workshop participants, and the project's target communities was particularly meaningful and rich in ideas. The communities did not expect that a group of practitioners from various European countries would take an interest in their areas. As a result, the impact was immediately positive and led to the development of new ideas and proposals, many of which came from the communities themselves and were realized during the open-site events. Notably, activities aimed at young blind citizens, co-organized with an association dedicated to promoting culture for blind people, were of particular importance.
- Many local, national and European institutions became involved during the execution of the project and expressed a willingness to be partners in similar future initiatives at the European level.
- Many professionals were challenged by the concept of turning the restoration process into a cultural event, which significantly contributed to skill development in this area.

Through the OPHERA Project, a technical-organizational model was developed. This model can be proposed again for future restoration site openings, not only in the countries involved in the Project but also in other European countries. In fact, the procedure for defining a capacity building team, sharing with local communities and restoration players, and defining opening projects and their implementation may well adjust to other scenarios, in particular in post-emergency scenarios where natural disasters occurred and where damaged cultural heritage assets can be made fit for use in a medium to long-term. The strengths of this model are certainly the team of operators involved, who must combine scientific expertise from research, artists, and restoration operators operating in the field. Expertise shall be distributed over a European area in order to define events capable of having a wider impact than the impact a local area where the assets being restored are located may have. The Project's community of cultural operators is already developing new initiatives in their towns that build on the technical-organizational model proposed by the Project.

The sustainability of the results achieved, meaning "the capacity of the project to continue and use its results beyond the end of the funding period", is certainly supported by the definition of the model described above. Through its group of operators and their involvement in the three capacity building workshops, the Project has laid the foundations to trigger processes of enhancement of the restoration sites even after the end of the Project itself. It has been demonstrated - and in this regard our dissemination activities are playing a key role - that a restoration process can lead to cultural enhancement and therefore produce the same direct and indirect benefits cultural development produces (e.g. economic benefits, better life quality, human development, etc.).

Project outputs also have the potential to produce a positive impact in the future. The lessons and workshops held during the three workshops will be available on the Project Coordinator's website. The materials produced for the exhibitions and events held during the so-called Cantieri Aperti (Open-Site Days) can be accessed from the Project and Partner's social channels. These materials have already been handed to the local authorities and sites owners. They will make permanent exhibitions at the sites in point, thus making the contents produced by the OPHERA Project accessible even after the restoration of damaged cultural heritage assets.

For all partners, the project was an important opportunity to share their priorities and expertise with new audiences, which helped create a sense of community and foster shared values. This will undoubtedly assist the entities involved in making better decisions in the future. Based on feedback received from all initiatives, both participants and the public found this project to be a valuable opportunity for personal and professional growth, so much so that several parties have expressed interest in repeating it.

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# Digital Tools for Assessment and Communication of Historic Architectural Heritage Restoration Project: The Case Study of Palazzo Saladini di Rovetino in Ascoli Piceno, Italy

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**Abstract.** The aftermath of traumatic events, particularly earthquakes, often results in the loss of community monuments for extended periods. This is due to the extensive damage caused by such events or the prolonged reconstruction process. Digital tools have the potential to accelerate the design and construction phases, while also facilitating communication of design intentions within the affected community. The use of these tools represents a significant advantage both in the survey phase, thanks to the speed of execution and the guaranteed safety conditions, and in the optimal management of project results. Virtual restoration allows the designer to verify the proposed interventions on a support that maintains as much as possible the morphological, material and tonal characteristics of the real artefact.

In addition, these tools allow a more effective communication of the status of the construction site also to a non-specialist public. In this context, the Ophera project, promoted by the Italian Ministry of Culture, adopted these innovative technologies and methodologies in the sites affected by the 2016 earthquake in the Marche region.

**Keywords:** Digital restoration · reality-based model · rapid survey tools

## 1 Introduction [1]

The occurrence of traumatic events, whether of natural or anthropogenic origin, gives rise to a range of impacts on human-made artefacts. Currently, historical architectural heritage is among the categories facing the greatest risk compared to other artefacts. This is primarily due to an increased awareness of the necessity of preserving historical heritage, as well as the inherent process of broadening the concept of heritage itself [2]. Another important factor is the rising danger to which the man-made environment is subjected due to climate change or the emergence of new destructive conflicts. Finally,


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society is becoming increasingly aware of the enhanced vulnerability and exposure of these artefacts due to inadequate maintenance or ageing of historical materials [3].

In the broader context of traumatic events, the earthquake certainly occupies a prominent place: this event often represents the moment when entire communities see the loss of their homes and the built environment in which they reside. The earthquake is thus configured not only as economic loss and social disaster, but also as deprivation of identity, destruction of symbols, loss of monuments [4]. It often happens that the post-earthquake reconstruction process is plagued by bureaucratic slowness or delays caused by the amount of work to be done in a small space. The present contribution proposes to address the tool of digital restoration as a decisive turning point in the design process, in order to optimise time, make the design effort more conscious and encourage communication of the results with the local community or other specialists. The OPHERA project, part of the contribution of which deals with the outcomes, intends to develop tools and methods that favour the accessibility of the lengthy reconstruction process to the general public and enhance the value of the restoration operations [5].

## 2 Rapid Acquisition Tools in Emergency Situations [6]

The utilisation of innovative digital tools during the survey phase confers a significant added value, as they facilitate efficient operations, considerably reducing working time and improving safety conditions, particularly in situations that are inherently delicate, such as post-earthquake scenarios. In such contexts, it is of the utmost importance that the accurate documentation of the state of the sites takes place before the execution of provisional works, as safety works often interfere with the correct acquisition of architectural surfaces. The utilisation of drone photogrammetry and time-of-flight (TOF) laser scanning enables the acquisition of high-resolution three-dimensional models, which are particularly advantageous when undertaking work on historic edifices or cultural heritage assets, where the capture of every detail is of paramount importance for the formulation of an informed intervention strategy. These methods offer not only greater precision, but also the possibility of collecting data in complex or dangerous conditions, thereby limiting the exposure of operators to risks such as collapses or falls. The effectiveness of these tools was demonstrated within the OPHERA project, which involved professionals with different skills in the field. The project promoted advanced data management and facilitated the communication of the restoration plan to local communities, thus fostering a constructive and informed dialogue on heritage restoration.

Terrestrial laser scanning techniques operate by measuring distances using a laser beam, which, through specific rotating optical-mechanical systems, is directed at an object while varying azimuth and zenith angles. The distance between the instrument's centre and the first point where the laser reflects back is determined by measuring the time it takes for the beam to travel. The distance, together with the knowledge of the emission angles, allows the determination of the point's position in polar coordinates. The survey involves placing the laser in multiple positions to ensure overlap between consecutive scans. Typically, the scanner is positioned 8–10 m from the previous and next stations to achieve this overlap. The result is a series of partial scans, later imported and merged using softwares like Leica Cyclone software. Scans are digitally merged, either manually or automatically, to create a dense point cloud with known X, Y, Z coordinates and reflectivity values. Since these points are collected based on the operator's parameters, data must be critically processed. The scanner used for the Palazzo Saladini survey is a Leica P40, capable of not only scanning the surrounding environment but also capturing an RGB image. This scanner includes a radiometric sensor to determine the colour of the laser-impacted points. Typically, these images are of low resolution and heavily affected by lighting due to lengthy scan times.

Photogrammetry in softwares like Agisoft Metashape is a multi-step process that produces a detailed 3D model from a set of photographs. The main steps used for Palazzo Saladini are as follows:

The initial and critical phase is the photo shoot, ensuring image quality for the final model. Photos are taken from different angles to cover the entire object or scene, with at least 60–80% overlap for effective alignment. Proper resolution and lighting are essential, avoiding shadows or overexposed areas. After acquisition, images are screened for focus, exposure, and distortion issues, discarding unusable ones. Selected images should cover all areas without gaps and with sufficient detail for accurate 3D reconstruction. The selected images are imported into Metashape, where compatibility checks are performed. Metashape supports various formats (JPEG, TIFF, RAW) and provides metadata management tools, including GPS data useful for geolocating the final model.

In this essential step, Metashape analyses photos to identify common reference points, creating a sparse point cloud representing an approximate scene geometry. Alignment settings can be adjusted for precision based on project needs and hardware capacity.Following the sparse cloud, the Dense Cloud is generated, adding detail to represent the object's geometry more accurately. Metashape provides quality options (low, medium, high) to balance detail with processing time, considering hardware requirements. The Dense Cloud points are then converted into a Mesh, a triangular surface network defining the 3D structure. Metashape offers various construction algorithms, like "Arbitrary" for complex objects or "Height Field" for terrain models. With the Mesh complete, a texture can be generated for visual detail. Metashape uses the original images to create a texture for the Mesh, giving the model a realistic appearance. Options include "Mosaic" and "Average," affecting quality and processing time. The final step involves optimising the model, such as Mesh decimation to reduce polygon count while maintaining visual detail for easier handling. The model can be exported in various formats (OBJ, FBX, PDF 3D), suitable for CAD, GIS integration, or 3D printing.

## 3 3D Approaches to the Conservation Project: The Digital Restoration [7]

The digitalization of the design process is an increasingly relevant research topic, especially in the field of restoration and conservation, offering a wide range of tools and methodologies [8]. This entails the need for a discussion on the possibilities offered by the use of new tools in relation to the requirements and established methodologies of the discipline. Indeed, it is crucial to emphasise that the formulation of the necessary outputs for developing a conservation project should not be dictated by the tools employed to generate them. On the contrary, research should focus on critically assessing digital technologies in order to understand their ability to effectively meet the needs of restoration projects. This also involves creating synergies between different tools [9], identifying and leveraging the potential of various available digital resources (such as BIM, photogrammetric models, and laser-derived models) to maximise each tool's strengths while compensating for their potential weaknesses [10]. The goal, therefore, is to take advantage of the increasing ability of digital tools to process data through the translation of the source into a system of information (and, consequently, connections) organised to fit the established theoretical and methodological disciplinary framework and not as a mere transposition of traditional content into digital format.

Digitalization goes along with the increasing need of reasoning in terms of 3D modelling, able to increase knowledge of buildings and allow better management of the design process [11]. A particularly promising line of research is that related to reality-based models [12], generally linked to digital photogrammetric modelling (but not only), to manage the materic and figurative aspects [13] of architecture that are a non-minor moment of the restoration project.

While many researches converge on the need to reinterpret BIM (Building information Modeling) systems to fit the needs of the built heritage, with highly promising results, the advantages offered by reality-based 3D models are equally significant and worthy of investigation. On one hand, these models allow the acquisition of complex geometries precisely and automatically, without requiring complex parametric or nurbs modelling techniques, while on the other hand they allow the collection of texture data in a photographic manner, which is particularly relevant in terms of reasoning related to the preservation and reintegration of architectural surfaces. The velocity of data acquisition and management, enabled by current softwares on the market, and the need for rather basic instrumentation, reducible in the last instance to a photocamera, make the production of photogrammetric models extremely easy and competitive even on a professional level.

Such models show further benefit when applied to emergency contexts where, thanks to the speed of execution and the possibility of deferring to a drone the most hazardous activities in contact with unsafe or poorly accessible buildings, they allow the operator to significantly limit risks and record crucial information for subsequent safety and restoration interventions.

The photogrammetric model, from being a simple partial product functionally used for the export of orthomosaics needed to characterise an architectural surface in a single plane of projection, can provide, once properly scaled to reliable metric data, the basis for mapping degradation pathologies through import into a 3D GIS environment [14], updating a tool already investigated in the scientific literature for mapping architectural elevations in 2D [15, 16]. Similarly, the mesh model can be imported into a management and rendering software to work through modelling and sculpting tools, as well as modifying textures, for the purpose of simulating the project outcomes in 3D. In this sense, the model becomes an additional methodological tool for governing the restoration project in relation to the chromatic, materic and conservative values of architectural surfaces, allowing a critically three-dimensional view throughout all design phases.

Managing the project issues directly on the model, involves that the production of 2D outputs generally required to interact with various figures (authorising institutions, other designers, construction site figures, etc.) and to enable the preservation of the data in a standard format, passes into a further stage, related to the visualisation and not to the production of the information. The production of the 2D drawings is in this sense an entirely ex post operation for which the 3D model provides a much more comprehensive and integrated basis than the 2D survey combined with the orthoimage. Also to this a posteriori phase can relate the transmigration of information processed on mesh model to an aggregative platform potentially constituted by the global BIM of the construction.

Through proper software, it is possible to deal with the various aspects that compose the digital architecture: from the morphology of the surfaces if altered or missing, to the insertion of ex-novo elements, to the management of the chromatic aspects of the textures up to the rendering of the lights. Moreover, when operating on fragmented architectural or sculptural elements, the same utilities allow for virtual recomposition attempts, to critically assess the validity of the operation before the physical recomposition.

### 3.1 Virtual Design Outcome Pre-evaluation of Architectural Facades [17]

The aforementioned tools of digital photogrammetry and laser scanning allow the elaboration of an extremely detailed reality-based digital model containing all the morphological and material characteristics of the architectural surfaces of a given building [18, 19]. In particular, the combination of three-dimensional mesh and photographic texture resulting from the digital photogrammetry process highlights the distinctive value of the adaptive orthophoto tool as a mapping mode for three-dimensional surfaces [20], generally available in the most common photogrammetry software. The adaptive orthophoto, as opposed to the simple orthophoto that privileges the surfaces parallel to the main plane of the architectural front in question, produces a mapping of all the surfaces of the mesh however they are oriented, maintaining the same quality as the photographic data and returning a textured model at every point with the same resolution [21]. As an example, an architectural façade characterised by many sculptural and protruding elements can thus be textured with the same photographic quality not only in the frontal surfaces, but also in the horizontal and sub-horizontal ones, where the preservation issues are most acute.

The crucial usefulness of an adaptively textured three-dimensional model was tested in the restoration project of the stone surfaces of the basilica of S. Salvatore dei Fieschi in Cogorno, Italy. The distinctive wall face in blocks of local calcarenite presented a peculiar type of scaling of the outermost layers, detached on planes parallel to each other and inclined relative to the cutting surface of the ashlar. This degradation morphology, best represented geometrically and materially by means of the textured mesh with adaptive mapping, required a careful evaluation of the yield of the planned reintegration and consolidation interventions on the detached surfaces, to be carried out largely with mortar grouting as well as with consolidating injections. The control of the chromatic and material rendering of the mortar fillings and of the reintegration of the joints was possible thanks to the special tools provided by the software, which allow one to operate on both the mesh and the texture. In particular, the mesh sculpting tools made it possible to smooth out the irregularities of the degraded surfaces, thus being able to assess the

**Fig. 1.** The pre-evaluation of conservational interventions on the facades of S. Salvatore dei Fieschi basilica's bell tower. On top: general comparison of the results of the digital restoration on a sector of the bell tower, before and after the editing. On bottom left: the texture before and after the digital elaboration by raster editing directly on the 3D surface. Below, the mesh before and after the sculpting process used to level and smoothen the surface, simulating the mortar fillings. On bottom right: postproduced visualisation of the final product.

new effect of the shadows on the restored wall face. At the same time, thanks to the possibility of operating directly on the texture of the 3D object with the classic tools of the brush and clone stamp, well known in the field of raster graphics software, it was possible to simulate and control the appearance and size of the mortar grouting, to the point of defining its shade and grain size according to the different types of stone found. The versatility and abundance of information provided by the adaptively textured model allowed a high degree of real-time control of the design outcome on the virtual model, in a proper example of digitisation of the architectural surface both in its current state of preservation and in the various design options evaluated (Fig. 1).

## 3.2 Reality-Based Models as Support for the Recomposition of Dismembered Parts [7]

As already mentioned, the use of a digital simulation of the restoration project is useful when working with dismembered elements whose recomposition needs to be designed by anastylosis. An exemplification of this methodology, widely discussed for quite a while in the specialised literature [22, 23], is given by the late mediaeval portal of the co-cathedral of S. Maria Argentea in Norcia, which was severely damaged by the 2016 earthquake. The portal was damaged by the collapse of a major part of the roof and the expulsion of the masonry parament, as well as by disassembly that became necessary during the process of securing. Recovered elements of the portal were arranged in pallets and transported to a storage facility, while some basement elements and those related to the backmost decorative band remained in place.

The photographic survey carried out from the ground, through the scaffolding, of all the elements in place, enabled the production of a photogrammetric model that, georeferenced on the point cloud (used to survey the entire complex), allowed for the effective characterization of the base to perform the reassembly. Next, the fragments in the repository were surveyed, differentiating the approach between the elaborately modelled parts (capitals and columns) and the simply shaped ones (bases and pillars), trying to employ the most optimised procedures according to the articulation of the fragments, relying also on the strategies available in the scientific literature [24]. For the first class of elements, it was opted for a detailed survey performed by structured light laser-scanner, while the other elements were placed on a stand and several dozen photos were taken for each element, producing a photogrammetric model of each element.

All elements were then imported into a modelling environment and catalogued, with each element assigned a unique code and its location on the pallet identified. Additionally, a description and approximate measurements were provided, following a methodology designed to facilitate the retrieval process during the construction phase [25]. All mesh models were imported maintaining the corresponding identification code in order to facilitate their individuation. The mesh model, thanks to the respondence in describing real geometries, permits the reconstruction of the complex puzzle, recognizing the margins of adhesion between the fragmented elements or between the elements originally pivoted. The morphological correspondence of the elements is combined with the photographic characterization of the texture, allowing the identification of chromatic elements of degradation (drippings, biological patinas) or the presence of oxalate patinas, facilitating the recognition of the adjacent edges of the fragments (Fig. 2).


**Fig. 2.** Some significant images regarding the damages and the project to rebuild the side portal of the Church of Santa Maria Argentea in Norcia. In image A, a photo of the portal before the earthquake. In pictures B and C the portal after the earthquake in a view and in the orthomosaic realised through photogrammetric modelling. In image D the photogrammetric model. Image F shows the portal fragments in storage. Images E and G show the reassembly of the catalogued pieces.

The virtual prefiguration of the intervention, made it possible to verify that the lacuna seen in loco, was fully restorable, since, following the digital reassembly, only two segments (out of fifty-three) were found missing, while almost the entire layout of the portal was present. The project therefore included the installation of new pins to re-anchor the elements to the wall, designing a filling of the small gaps with slightly simplified stone patterns, significantly reducing the margin of ambiguity in the design stage.

### 3.3 Digital Tools for Interior Restoration and Lighting Prefiguration [7]

Dealing with spaces where the decorations are particularly rich and the surfaces have complex geometries, especially if affected by conspicuous structural decomposition or material degradation, a modelling based on photographic data has undoubted advantages. In the case of the Church of the Resurrection in Santa Vittoria in Matenano (FM), the main liturgical environment presents a rich baroque stucco arrangement mainly concentrated in the back half of the hall, where a survey campaign allowed in 2021 to elaborate a digital photogrammetry model of the entire environment. The surfaces, although very decorated, have lost all the chromatic traits due to degradation as well as a series of white re-paintings that obliterated the original colours of the hall. The church is also poorly lighted due to the infill of two windows at the back of the presbytery, reducing the perception of the architecture. Lastly, the flat coloration extended to the entire Baroque stucco contrasts with the stratigraphic windows opened in the lower part of the church in the 1980s to reveal some valuable mediaeval frescoes, which consequently visually prevail over the rest of the architecture.

In order to manage a project aimed at enhancing the architectural layout, currently disharmonized and flattened in a sort of desire to negate the Baroque phase in favour of mediaeval inserts, an attempt was made to exploit the 3D model as a tool for prefiguration and preliminary evaluation of the intervention. By working on isolated surfaces brought together in a global model, it was possible to work on the textures, processed in adaptive mode, which were edited as raster to conjecture new chromaticity that would return a better readability of the layout.

Equally valuable was the digital modelling intervention, which not only allowed the reintegration of missing sculptural parts but also enabled a preliminary hypothesis for reopening the 17th-century windows.

The model has been used to study the design possibilities with a detail level able to prefigure the intervention in a nearly instantaneous way, experiencing through simulation the effectiveness of the design, especially concerning the modification of the spatial reading thanks to the light coming from the reopened windows. Equally, a lighting system was proposed to illuminate the vault diffusely, avoiding strong chiaroscuro that would interfere with the reading of the minute chisels of the decorations. The possibility of viewing the model in an immersive way, through the export of videos and 360-degree images, allowed for a proactive evaluation of the design scenarios, enabling adjustments when the results did not align with the set objectives. This process uses the digital model as a verification tool that provides an immersive and realistic prefiguration of the design outcome, which is far more reliable than any manual modelling in terms of both colour


**Fig. 3.** The use of reality-based mesh models has considerable advantages in the rendering of a design hypothesis. In particular, the series of images proposed explicate how the simulation of the reopening of the windows and the proposed chromatic reintegration of the stuccoes of the Church of the Resurrection of Santa Vittoria in Matenano, also associated with the design of a new lighting system and new furnishings, allows to use the model to verify various solutions in a photorealistic manner. Below is a perspective section of the hypothesised project state.

**Fig. 4.** On top: a prospective view of the point cloud of Palazzo Saladini. At the centre: an orthophoto of the vault of the Galleria degli Specchi. On the bottom: an orthophoto of the main façade.

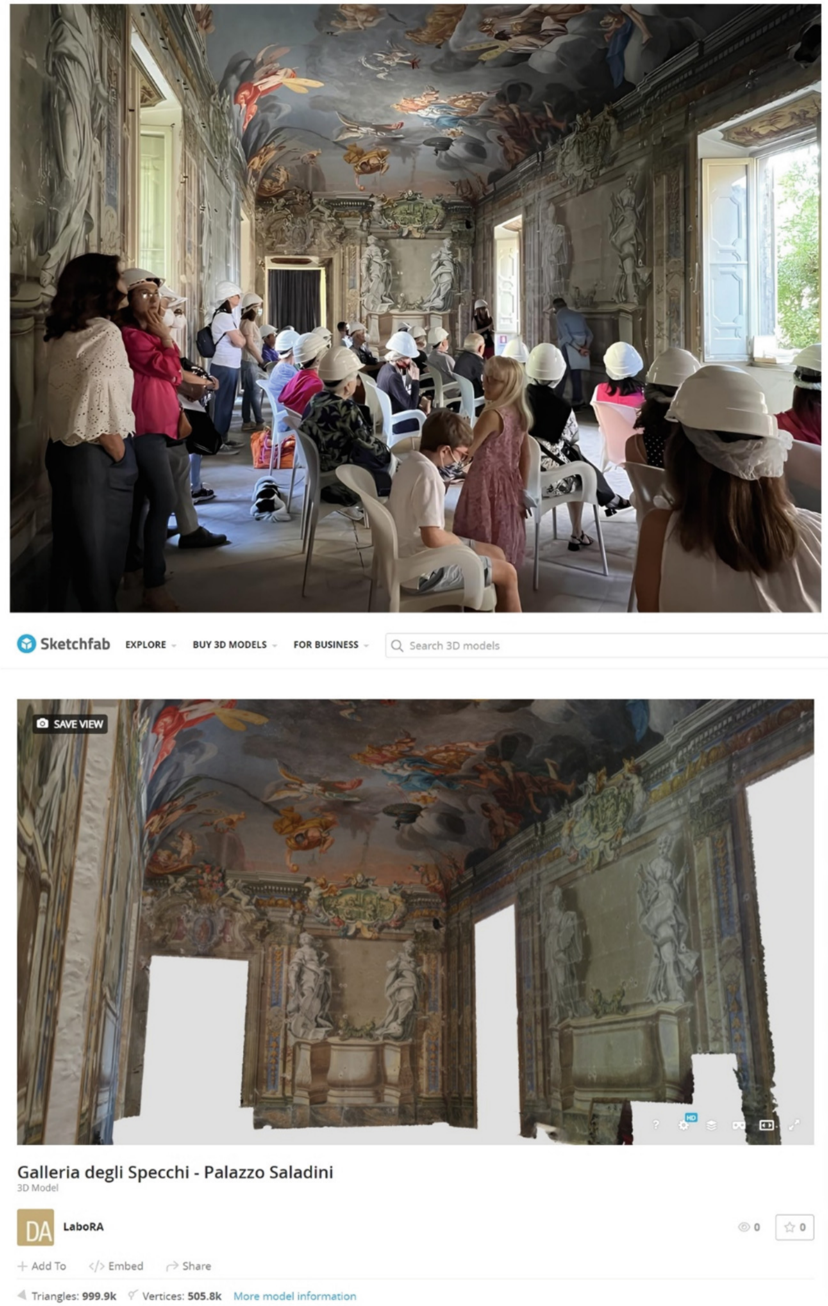


**Fig. 5.** On top: a shot of one of the "Cantieri Aperti" events with specialist talks and musical episodes. On the bottom: the textured model of the Galleria uploaded to an online model viewer.

accuracy and geometric precision, all while requiring minimal effort from the operator (Fig. 3).

Whereas the model, thus configured, provides a way to prefigure the intervention and stand as a critical tool for designers, nevertheless it is also possible for it to be enriched with additional information, eventually simulating reconstructive phases, with the aim not of prefiguring an intervention, but of standing as a potential tool for cultural heritage enhancement, according to a method widely used in numerous contexts [26].

## 4 The Case Study of Palazzo Saladini di Rovetino in Ascoli Piceno: From Survey to Design Outcomes Communication [1]

In 2018, the Regional Secretariat of the Ministry of Culture for the Marche Region, aware that the restoration of cultural heritage and the reconnection between communities and territory are long-term processes, launched the project "OPHERA – Apertura del patrimonio culturale alle comunità durante il processo di restauro post-sisma 2016: tecnologie digitali e nuove competenze per gli operatori culturali", co-financed by the European Union's Creative Europe Programme. The primary aim of the project is to make part of the damaged cultural and historical-artistic heritage accessible throughout all phases of the restoration process, using both traditional and advanced interactive tools [27].

The project seeks to promote a cultural exchange between restoration professionals and a heterogeneous public, consisting of citizens, tourists, local administrators, students and cultural associations, through the creation of a European team of cultural operators and artists. In particular, the initiative envisages the organisation of a series of events, called "Cantieri Aperti" (Open Sites), in the Marche crater area, with the aim of transforming the restoration process into a shared cultural experience.

One of the locations examined by the project was Palazzo Saladini di Rovetino in Ascoli Piceno. It was constructed between the end of the 17th century and 1719, probably on pre-existing structures, with three floors above ground and a roof-terrace.

The edifice features a principal façade softened by Baroque cornices, an internal courtyard, and a notable frescoed hall on the first floor, called Galleria degli Specchi (Mirror Gallery). This rectangular room, covered by a flat vault, is entirely covered with paintings by the local painter Biagio Miniera (early 18th century), which were recently discovered under false walls and ceilings [28]. The building is in need of structural conservation and restoration work on the interior and exterior surfaces. It is included in the ADSI Italian Historic Houses circuit [29].

The operations conducted on the edifice were divided into two principal categories. Initially, a laser scanner and photogrammetric survey were undertaken on both the interior and exterior of the structure. Subsequently, public open days were organised, during which visitors were afforded the opportunity to explore the building in the company of architects and restorers.

The morphological acquisition campaign by laser scanner involved the exterior elevations, the interior courtyard and the most relevant spaces inside the building, including the Galleria degli Specchi and the Altana. Photogrammetry, on the other hand, was conducted with drones for the main façade and with the aid of a hand-held reflex camera in the Salone. The textured three-dimensional models generated were subsequently scaled and oriented in relation to the point cloud obtained from the laser scanner survey. As previously discussed, the textured mesh represents an essential basis for an accurate restoration project; in this specific case, it also supported the enhancement of both the historical architecture and the future restoration site. In recent years, several online platforms allow visualisation and interaction with three-dimensional models, also integrating immersive or augmented reality features (such as Sketchfab, Nira.app, Turbosquid, etc.). For instance, the mesh of the Galleria degli Specchi was uploaded online, offering those who could not attend meetings the possibility to explore it in high definition or to virtually immerse themselves through 3D viewers (Fig. 4).

Similarly to the case studies of San Salvatore in Cogorno and Santa Vittoria in Matenano, the textured model provided a fundamental basis for demonstrating the potential of digital restoration in real time during the opening days of the palace. The adaptive texture was loaded into raster editing software, allowing the application of typical interventions on the decorated surfaces, such as dry cleaning, consolidation, material and pictorial reintegration and protection. This process allowed visitors to visualise, in a three-dimensional environment, a simulation of the final state of the Galleria post-restoration.

In June 2022, Palazzo Saladini was one of the venues of the "Cantieri Aperti" events. The initiative, realised in collaboration with the owner of the building, ADSI and the Municipality of Ascoli, offered an in-depth examination of restoration issues through a number of interventions by the main actors involved in the process, including designers, restorers and conservation officers. These contributions related the roots of the restoration concept to the specific choices made for the building's Galleria. To accompany the presentations, short musical pieces were performed by the students of the Gaspare Spontini Musical Institute (Fig. 5).

## 5 Conclusions [1]

In the context of traumatic events, such as seismic phenomena, historical architectural heritage is particularly vulnerable, exhibiting greater damage than other categories of assets. The utilisation of rapid digital survey instruments is advantageous in a multitude of ways. From the perspective of operator safety, the acquisition of data can be conducted without direct contact with the portions or environments at risk of collapse. Additionally, the speed at which the survey can be completed is a significant advantage: it is crucial to obtain the data before starting the safety works, which present a significant challenge in the management of earthquake-damaged sites. Furthermore, from a methodological standpoint, the three-dimensional component of the data surveyed merits particular attention. This last factor is relevant for subsequent phases, as the possibility of maintaining detail and three-dimensionality throughout the entire project chain can bring advantages both to the outcome of the site and to the valorisation of the project itself in the community where it is embedded.

Nevertheless, numerous deficiencies persist. For instance, a protocol is lacking among professionals (at least within the conservation domain) to facilitate genuine interoperability between technicians. Additionally, the formalisation of three-dimensional processing for degradation phenomena and interventions remains an unfulfilled necessity. The two principal operational strands are based on technologies that are currently not particularly communicative. On the one hand, BIM has certain rigidity issues associated with the management of reality-based models, which precludes or limits parameterisation. On the other hand, 3D GIS is constrained by its purely territorial nature, which forces it to deal with frequently vertical architectural surfaces or even sculptural details. It is yet to be seen whether these areas of ambiguity within the process will be fully and harmoniously resolved in the future.

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# Preserving and Communicating a Sudanese Heritage Site Through a Digital Exhibition

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**Abstract.** Archeological activities in Sudan have been threatened by political instability and violence, putting its rich heritage sites and their documentation at risk of being damaged or lost. This chapter presents the case of Al-Khandaq town, a major archeological site that documents Sudanese architecture and cultures across several centuries. The town, in the UNESCO 1972 Convention tentative list, had been almost nonexistent in the online domain, having only a short Wikipedia page devoted to it and a few technical mentions or images. Moreover, most of the available documentation has been destroyed by the militia raiding the University of Khartoum. However, based on the data recorded on the laptop of the director of excavations, it has been possible to document this site and to provide a first digital representation of its fascinating architectural history. The presented digital exhibition, published on Google Arts and Culture, is not only important as an instance of digital preservation, it also provides an example of how digital assets can be orchestrated in a co-creative fashion, involving university students in its design.

**Keywords:** Digital Archeology · Digital exhibition · Digital preservation · Heritage communication

## 1 Introduction

This chapters presents the making-of a digital exhibition on the Sudanese archeological site of Al-Khandaq and its Architecture[1], which has been developed as a way to preserve and communicate it in a highly dramatic national context, in which archeological remains, their documentation as well as involved researchers have been put at risk due to the conflict.

Moreover, the case provides a vivid example of how the building of a digital exhibition might be done involving several partners, including university students that, in doing so, at the same time learn about archeology and about digital exhibitions (design), a learning-by-doing that is likely to be very memorable for them and their future careers.

[1] https://artsandculture.google.com/story/OAVxtZbipkH5xQ.


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Documenting an almost unknown archeological site on a highly visible digital platform might, eventually, lead to an increase in awareness and in dreaming about visiting it, which is the very first trigger of heritage tourism…

The chapter is organized as follows: the next paragraph (n. 2) will provide a brief overview of the town and of its very rich history. Paragraph 3 provides some context about how digital media can be orchestrated not only to support documentation, preservation, and conservation, but also to support communication and for tourism purposes. The next paragraph (n. 4) details how the digital exhibition has been designed and developed, as well as how it is being evaluated. Some final remarks conclude the chapter and suggest possible future research and development itineraries.

## 2 Al-Khandaq, Its Rich History and Legacy

Al-Khandaq is situated about 423 km north of Khartoum on the left bank of the Nile. It was a well known town and large village in the early 18th century; its name has been on maps since 1725. Al-Khandaq has been written in many ways: Handak, Khanduq, Hendek, Hhandac, Khandak or Hellet al Handak. It has been described as one of the best built towns in Nubia (Stacy, 1959). It is one of four places of any note to be recorded with North Dongola, Handak, Old Dongola and Debba, and was the residence of many rich merchants who built good houses (Hill, 1959). By the early 20th century, Al-Khandaq was already one of the six Mamaurias (districts) of Dongola Province: Dongola, Khandaq, Argo, Meroe, Korti, and Debba (Budge, 1907). As MacMichael told by Daud Kubara in 1911, it was one of the ancient glories of Nubians along with Old Dongola Argo, Sai, Wadi Halfa, Faras and Ibrim (MacMichael, 1967).

Budge has taken Al-Khandaq's history back to 1000 BC, when it was one of the New Kingdom (1450–1100 B.C) settlements along with: Kalabsha, Delgo, Tumbos, Argo, Old Dongola, Meroe and Jebel al-Barkal. A temple of Amenhotep is alleged to be in Khandaq, now located under a mosque. (Crawford, 1954) referred to a mosque which has been built on the ruins of a Christian church. Arkell (1961) dated the fortress to 1250–1340 during the Christian period when Makuria was in the defensive state though evidence from the pottery dates it back to the 7th century AD. From Abu Salih the Armenian, reported the existence of a monastery of St. George where the Nubian King Solomon was alleged to be buried (Shinnie, 1984).

During the Funj period 1504–1821, it was the headquarter of Al-Khandaq "mekdom", one of the four mekdoms affiliated nominally to the Funj King (1504–1820). During the Turkiyya (1821–1885) and Anglo-Egyptian rule (1898–1956), Al-Khandaq has been one of the main districts of Dongola Province due to its urban setting (Budge, 1907). According to British reports, the town had schools with 50 students, permanent buildings such as a police station, rest house and post and telegram office (Soghayroun, 2014).

### 2.1 Current Situation

The fort, or the "Qaila Qaila" as it is known locally, dominates the town: its southwest tower is visible from both north and south, whilst its western wall, with the remains of the south western and interval towers, dominates the area, looking from the west. The northern wall, which runs east-west, has largely disappeared and is cut off by a track used by the town's people and their animals, at its eastern end. It seems that most of the stone has been reused to build the police station in the early 20th century and later some of the houses. Further adding to the destruction of the site is the presence of large quantities of animal dung inside the fort, which the local people excavate to use as fertilizers.

The public buildings include the police station, which was established in 1902 and still survives. However, the post office and customs house no longer exist. The remains of the old butchery are still visible to the north of the boys' elementary school. The indigo factory is represented by large granite stones and traces of the basins, but the main area has been used for cultivation. Established in 1905, the resthouse which overlooks the river from its high position is still standing but is in urgent need of restoration. The surface pottery sherds date back to the Christian and Islamic periods.

The town's houses with their size and quality confirm the distinction of the town as the residence of wealthy merchants; these have been deserted since the early 1970s when trade declined and the merchants moved to Khartoum and Omdurman. There are two mosques in use: el-Hassanab and el-Khatibiya. The el-Hassanab's minaret is free-standing, whilst the other mosque's minaret is an integral part of the building. There are as well some of the domed tombs of Muslim sheikhs.

Al-Khandaq was a primary port on the river between the 17th and 20th centuries connecting western Sudan with the river. It was described by the early travelers as one of the best-built towns in Nubia and was the residence of several rich merchants who resided in unique two-story mud brick houses. The site began to decline during the 1940s as the port faced increasing competition from the railway and road traffic as goods carriers.

## 2.2 Cemeteries

One of the observable features of the town is the presence of several graves everywhere, inside inhabited houses, along the roads, beside the graveyards; this includes burials with vaulted roofs, group burials (*Toskiya* is the local term) and others tunneled into limestone hills (concealed graves). It seems that the town of Al-Khandaq was built upon a large cemetery. There are two royal cemeteries, and the main town cemetery is divided spatially among many factions of the town, i.e.: Hassanab, Musiab, etc. and naturally by gullies. Grave superstructures vary. There are ordinary oval-shaped graves with two tombstones, inscribed and plain, with stone pebbles scattered on their surface; some have a sort of low mastaba of red brick, or mud brick, again with tombstones. Others are surrounded by a mud or mud-brick enclosure with a height ranging between 200–500 mm (Soghayroun, 2004).

## 2.3 Oral Tradition and Community

Oral tradition supports written documents describing caravan leaders, sailors, liquor stores, canteens, and the shops that once lined the riverside road. Documents uncovered at the site and those kept at Bergen University disclose the commodities traded and the famous traders and routes. The accounts detail, for example, the house in which the Mahdi army leader stayed briefly before resuming his march to the North. Many commercial documents, contracts, letters, promissory notes, and receipts have been found, which testify to the broad and far-reaching trade activities carried out by the Khanadqa, even during its decline.

Al-Khandaq's inhabitants follow a different lifestyle from the rest of the country (Soghayroun, 2014). They perceive themselves as different from those surrounding them. Oral history collected from elders, males and females, by the excavation team in the period between 2006–2013 revealed the role of the valleys (called *Widyan in Arabic*) in the flow of people, ideas, and cultures, suggesting to search for traders from al Khandaq that dispersed in different parts of the country and to approach the effects of the diaspora. The widyan created a trade network between the desert and the Nile. Additionally, the widyan offered safe and comfortable routes for trade caravans (Soghayroun, 2009).

Al-Khandaq is a mingling pot for people from inside and outside Sudan. The prestige of Al-Khandaq leads people to identify themselves as exclusive residents of Al-Khandaq, not to a tribe or the place they came from. Oral history mentions that its residents came from al-Hudur, from the urban centers. Others came from Egypt before the Turkish invasion or from other trading places along the Nile (Budge, 1907). Reference has been made to Yemen and Morocco as their origin as well. Regardless that Al-Khandaq locates in the Dongolawi language region, its inhabitants speak Arabic, the trading language during the Christian and Islamic kingdoms. (Trimingham, 1965).

Documents have revealed the role of female traders in Al-Khandaq. Women were also merchants who traded different items through mediators. Women lent money and finance mortgages. Women also prepared containers made from palm branches and wheat stalks, which are lightweight and allow for air to penetrate, keeping the foodstuffs in good condition for long journeys. They also prepared water skin and leather bags, dried meat, spices, and dried bread (*kisra* or *abrai*). Women were, and continue to be, the main customers of nomads who brought the white lime from the widyan plateaus to paint walls. The women of Al-Khandaq extract lime from within the town outcrops. They use yellow lime to pave floors or make standing free hearths and cooking ovens.

Their economic prosperity from long trading experience furnishes them with the necessary wealth to educate their children, and according to documents uncovered at some of the deserted houses as well as information from local informants, most of the Khanadqa assumed high positions in the government and the percentage of literacy is high. Documents uncovered show the type of books, magazines, and journals they received during the early 20th century. According to British reports, the town had schools with 50 students (Hill, 1959:127).

## 2.4 Registration in the UNESCO Tentative List

Al-Khandaq was registered in the Tentative List of the World Heritage in 2022, suggesting that it reflects three criteria of Outstanding Universal Value (OUV), being one of the best-preserved integral villages built with remarkable mud brick architecture in Sudan and sub-Saharan Africa; furthermore, it exhibits an important interchange of continued values for more than three thousand years, from the New Kingdom till the independence of Sudan.

An initial assessment of Al-Khandaq's intangible cultural heritage has unveiled a significant aspect of its culture – namely, its vibrant and diverse heritage. This encompasses oral traditions, performing arts, social practices, rituals, and notably, the art of weaving. Indigenous communities continue to embrace these traditional cultural expressions, especially during marriage and circumcision celebrations, as well as funeral rituals. These practices maintain a profound connection to the Nile and Al-Khandaq's historical monuments, with roots extending back thousands of years, possibly to the Kushite period.

Furthermore, the abundance of intangible cultural heritage in Al-Khandaq is attributed to its historical significance as a crucial river port along the Nile. It served as a hub for people and goods from northern Sudan, Egypt, and beyond, facilitating exports and imports from the heart of Africa, especially Kordofan, Darfur, and southern Sudan. This interaction of diverse groups, bringing their heritage with them, has molded customs and traditions unique to Al-Khandaqi communities over centuries. These distinctive practices contribute to the special character of the cultural heritage found exclusively within the Al-Khandaq region and therefore merit urgent safeguarding, especially considering the current circumstances in Sudan.

## 3 Digital Media, Tourism and Cultural Heritage

The internet has contributed to deeply transform the dissemination of information, transcending geographical boundaries and device limitations (Cantoni & Mele, 2022). With appropriate intentions and applications, digital media can facilitate global connectivity and foster engagement across different audiences (De Ascaniis & Elgin-Nijhuis, 2022). In the realm of digital preservation (Ioannides et al., 2021), these technologies prove instrumental also in raising awareness and inspiring potential tourists. Cantoni and Mele (2022) also highlight that digital media can create anticipation and attract visitors to heritage sites.

In the case of Al-Khandaq, the primary goal of the presented project extends beyond merely preserving and documenting; it focuses on creating an intriguing experience and showcasing the town's heritage also for those who are not archeology experts and might be, once it is possible, interested to visit Sudan.

If we consider the interplay of all above-mentioned elements, we can see three distinct realms: Information and Communication Technologies (ICTs), Cultural Heritage, and Tourism. The integration of these fields generates a distinctive communication experience for users (Cantoni, 2020: 238).

There is a growing interest in digital platforms, particularly in open content publications, which make data available for reuse by others, be they researchers or just interested people. Although the relationship between tourism and cultural heritage is well documented, the intersection with ICTs requires further exploration. Notable projects, such as a digital exhibition on Macchu Picchu (Picco-Schwendener, 2022), have already started to explore this intersection: the Al-Khandaq project aims to contribute to this evolving field.

Two key research and development areas in these overlapping fields have been identified: one focuses on preservation and conservation, while the other one emphasizes communication and presentation (Cantoni, 2020), communication is essential in connecting these aspects, as a "major transversal element" (Cantoni, 2020: 243).

In the case of Al-Khandaq, a digital exhibition serves as a means to share and to disseminate the town's rich cultural heritage, especially during so challenging times in the region. The goal is to raise awareness of the beauty and history of Al-Khandaq, promoting the town in anticipation of Sudan reopening its borders to tourists.

The use of Google Arts & Culture (GA&C) as a digital technology medium offers several advantages. As noted by Cantoni and Mele (2020), digital technology makes information widely accessible and flexible, allowing for continuous updates, improvements, or reinterpretations. Additionally, digital platforms are interactive, engaging users with the content, and customizable, which enables tailored communication to specific audiences, thereby boosting user engagement and appreciation. Publishing on this platform does not require any financial investment, making it affordable also for low-budgeted projects; moreover, GA&C is likely to support its contents over time, addressing the obsolescence of digital media, a major challenge that requires constant (and expensive) updates.

It must be said that GA&C is also a medium that can create opportunities "that allow people to overcome worldwide restrictions, by travelling again with their minds and (re-)connecting with heritage" (De Ascaniis & Elgin-Nijhuis, 2020). This explains the decision of using GA&C as a medium for the preservation and narration of the history of Al-Khandaq. By employing these technologies, the project aims to enhance awareness, facilitate effective communication, and safeguard cultural heritage.

## 4 Designing and Developing a Digital Exhibition

Although it was specifically developed to design instructional activities, the ADDIE model – Analysis, Design, Development, Implementation, and Evaluation (Branson et al., 1975) can be easily adapted to design products and processes in various other domains, including digital exhibitions (Stachel & Cantoni, 2024): its flexible and systematic approach to design ensured a comprehensive and structured process also throughout the project of the Al-Khandaq digital exhibition.

### 4.1 Analysis

The initial phase of the project involved students from the course "ICT for Cultural Heritage", taught by Stefano Tardini and Lorenzo Cantoni at the Bachelor in Communication at USI – Università della Svizzera italiana (Lugano, Switzerland) in the academic year 2023–24. Their task was to design a first draft of the digital exhibition, formulating hypotheses, identifying potential publics for the online exhibitions, and assessing the affordances offered by GA&C.

Students were briefed by Ahmed Adam, the field director and archaeologist for the Al-Khandaq project, who met them also during the semester, sharing all images he had kept on his laptop while leaving Sudan. Additionally, access to Intisar Soghayaroun, the principal director of the Al-Khandaq project and a pioneering archaeologist in Sudan, was offered through videoconference. Students worked in two groups, supervised by one of the two instructors, and then provided their proposals for a digital exhibition in a final presentation.

The outcomes of their final projects and presentations provided foundational materials for Susanna Phan, an intern at USI's UNESCO Chair. Phan's task was to analyze these materials, generate developmental ideas, and select unpublished photographs for the exhibition.

### 4.2 Design

In this second phase, Ahmed Adam, Susanna Phan, and Lorenzo Cantoni, holder of the UNESCO Chair in ICT to develop and promote sustainable tourism in World Heritage Sites at USI[2], established the framework for the exhibition, integrating the students' contributions into a single narrative structure.

The exhibition was in fact segmented into four distinct chapters:

- *Introduction to Al-Khandaq:* An overview of the town, its significance, and context.
- *Architectural significance:* Exploration of the factors that led to Al-Khandaq's inscription on UNESCO's tentative list, with a focus on its architectural features.
- *Cultural Diversity:* Highlighting the "Khandaqawi" people and the town's cultural diversity.
- *Conclusion and future outlook:* A summary emphasizing the hope for Al-Khandaq's future prosperity, which might also be connected to attracting tourists.

Subsequently, Intisar Soghayaroun contributed in refining the exhibition's content. Her extensive documentation of Al-Khandaq's history provided crucial insights that enhanced the exhibition's accuracy and depth.

### 4.3 Development

The development phase involved several key tasks:

- *Photograph selection:* High-quality unpublished photographs among those made available by Ahmed Adam were chosen to enrich the exhibition. The absence of copyright issues facilitated the selection, ensuring a visually compelling presentation on the GA&C platform (Cantoni & Mele, 2022).
- *Timeline Creation:* Due to the extensive history of Al-Khandaq, presenting all historical content in a single format was impractical. A timeline was developed to segment the history into three periods – pre-history, medieval and post-medieval, and modern history. Multiple drafts were created, with the final version optimized for GA&C as a 2000x2100 pixel image. This timeline (Fig. 1) incorporated brief descriptions and images of key features visible in Al-Khandaq today.

2 https://www.unescochair.usi.ch/.

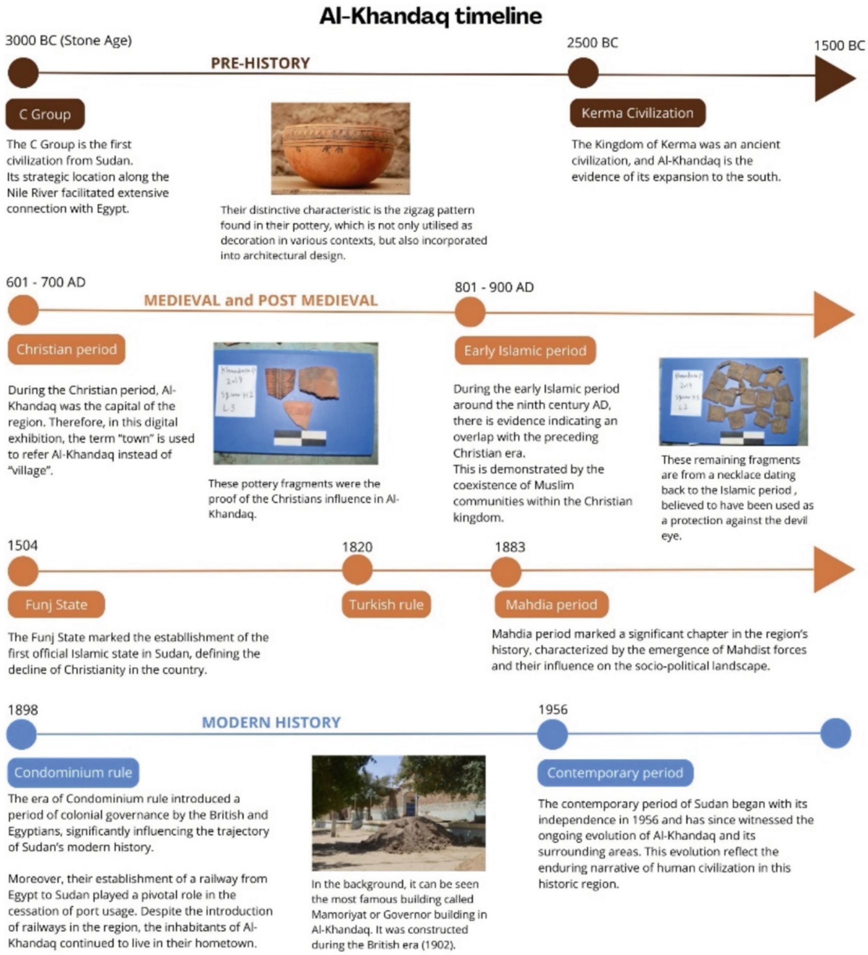


**Fig. 1.** Al-Khandaq timeline. Source: authors.

- *Multimedia Integration:* To enhance engagement, two introductory videos were produced. The first featured Ahmed Adam introducing the exhibition, while the second one used Google Earth to provide a virtual overview of Al-Khandaq. These multimedia elements aimed also to highlight the collaboration between USI and the University of Khartoum in this project, fostering a cross-institutional connection.
- *Language Considerations:* The exhibition was made available in Italian and English. Italian was chosen due to USI's location in an Italian-speaking region, and English was selected for its broad academic and global reach. Unfortunately, due to time constraints, the inclusion of Arabic was not feasible, however, GA&C provides automatic translation in several languages, making the exhibition accessible well beyond the two original used languages.

### 4.4 Implementation

In the implementation phase, the developed content was integrated into the GA&C platform. This stage required careful attention to ensure that the exhibition's layout and multimedia components functioned seamlessly across different devices and screen sizes, in particular on laptops and on smartphones.

According to its procedures, the digital exhibition was then tested by GA&C and then released on the platform (Fig. 2).


**Fig. 2.** Cover image of the digital exhibition. Source: authors.

### 4.5 Evaluation

The exhibition has been launched online in May 2024, hence it is still quite early to attempt an overall evaluation of it. However, the Evaluation steps have been planned to include both users' feedback as well as digital analytics.

In the first months, two activities have been performed:

- *Presentation Feedback:* the digital exhibition was presented during the "Research Talk", a weekly meeting for PhD students, researchers and professors at USI's Institute of Digital Technologies for Communication. Participants provided relevant feedback and suggestions for improving the exhibition as well as its promotion and visibility.
- *Usages:* the statistics offered by GA&C have been used to assess the exhibition's reach and to get some info about its users. In the first months, until September 2025, the digital exhibition has been visited by 385 users from 29 countries (the five most represented being: Switzerland, Italy, Spain, Germany, the USA). The average visit

duration has been of 227 s, hence more than 3′30′′, which provides evidence of a significant interest to explore the exhibition in detail; however, the distribution was not even, having visitors staying some seconds and some others staying much longer.

Further and finer analyses will be performed in due time, when also promotional initiatives will be performed to ensure a wider knowledge of the exhibition by the concerned communities of researchers, students and other stakeholders.

## 5 Conclusions

The war which started in Sudan in April 2023 has caused vast destruction, which has sparked widespread vandalism and looting as most of the heritage, including museums, theaters, and archives is in one way or another damaged including some of the regional archaeological and heritage sites. Thus, it became a difficult and daunting task to do map Sudan's rich cultural and historical heritage, and assess the damage it has sustained since the onset of the war: as an example, as of September 2024 about 15 museums, including three in Khartoum, three in Darfur and one each in North Kordofan and Gezira, have been heavily ravaged by fighting, especially the Khartoum Museum, because it is located in the battle zone of the war, whereas the National Museum houses the country's largest archaeological collection located in the very heart of the nation's capital, an area hard hit by the fighting.

The effective protection and conservation of the historical buildings will provide fundamental assets for cultural tourism and community-based tourism to (re-)develop, as soon as a stable peace and security will be available.

Part of such efforts can be done through digitizing materials and making them available to all interested parties, an activity where Sudan is still lacking behind, and where this project can provide a relevant example for others to follow.

We believe that our project could contribute to a better knowledge and preservation as well as to a larger communication of Sudanese heritage, in view of better and brighter times in which it will be accessible to researchers and to domestic and international travelers alike. The acquired income from tourists might eventually enable the responsible institutions to develop regular monitoring systems to manage this and other sites.

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# Digital Heritage Documentation for Protecting and Rebuilding Tangible Heritage in Natural Disaster and Conflict Zones

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**Abstract.** The article explores the role of digital heritage documentation in safeguarding and reconstructing tangible heritage—both movable and immovable— in conflict areas also prone to natural disasters. Through a series of case studies and examples generated by the Digital Heritage and Innovation in Cultural Heritage (DITCH) incubator, the research emphasizes the importance of integrating smart methodologies and modern technologies into cultural management strategies in post-disaster and conflict settings.

**Keywords:** Digital Heritage Documentation · Cultural Management Strategies · Photogrammetry · 3D Models/Digital Twins · Preservation and Restoration

## 1 Cultural Management Strategies

In environments recovering from disasters or conflicts, the preservation of cultural heritage faces unique challenges. The destruction of heritage assets results not only in a loss of historical artifacts but also in a fragmentation of cultural identity [1]. To address these issues, cultural management strategies must evolve by leveraging smart methodologies that incorporate technology, collaboration, and resilience. The integration of documentation, digitization, and innovative preservation techniques is essential for both immediate recovery and long-term sustainability. By applying these approaches, tangible cultural heritage can be safeguarded, restored, and made accessible for future generations, even in the most precarious circumstances.

### 1.1 The Role of Smart Methodologies in Post-disaster Cultural Management

Smart methodologies in cultural management leverage emerging technologies and strategic processes to document, preserve, and enhance access to cultural heritage. These approaches are particularly critical in post-disaster contexts, where both resources and the physical integrity of heritage assets are strained. Advanced tools such as 3D scanning, photogrammetry, Geographic Information Systems (GIS), and digital repositories offer powerful solutions for preserving heritage in uncertain conditions [2]. For example,


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after the 2020 Beirut Port explosion, the AUB Archaeological Museum in collaboration with the Mechanical Engineering department both at the American University of Beirut quickly adopted digital tools to assess damage and initiate recovery efforts [3]. Photogrammetry enabled the creation of highly detailed models of damaged artifacts, buildings, and archaeological sites, providing precise documentation for restoration planning. This process not only facilitates physical recovery but also ensures the preservation of accurate digital records that can serve future generations [4].

GIS plays similarly critical role in managing the spatial aspects of heritage conservation in post-disaster contexts. By mapping the geographical distribution of heritage sites, GIS enables cultural managers to assess vulnerabilities, prioritize interventions, and monitor the ongoing condition of sites in real time. This dynamic approach to spatial documentation allows for better-informed decision-making, particularly when resources must be allocated efficiently [5].

### 1.2 Digitization for Preservation and Access

Digitization is a cornerstone of smart cultural management methodologies, ensuring that even in the face of disaster, heritage can be preserved digitally. By converting physical artifacts and sites into digital formats, institutions create resilient archives that transcend the limitations of physical preservation. In conflict zones or areas prone to natural disasters, these digital archives act as a safeguard, reviving cultural heritage from destruction, as was the case with the archaeological site of Palmyra and the Buddha statues of Bamiyan.

The digitization process extends beyond simple preservation. Digital archives allow heritage assets to become more accessible to a global audience. In regions where recovery may take years or decades, digital representations of cultural objects can be shared with scholars, educators, and the public, promoting continued engagement with the material even if physical access is restricted. This has the added benefit of democratizing cultural heritage, making it available to diverse communities worldwide [6].

A notable example is the Syrian Heritage Archive Project[1] which used digital tools to document and preserve Syrian heritage during the ongoing conflict. The project compiles photographs, maps, and written documentation into a comprehensive digital archive, ensuring that Syria's rich cultural history remains accessible, even while physical sites are under threat.

The future of cultural management however, lies in exploring cutting-edge technologies beyond traditional methods. Artificial intelligence (AI) and machine learning are increasingly being used to predict the structural deterioration of heritage sites, allowing for proactive intervention [7]. Similarly, blockchain technology offers potential for securing the provenance of digitized artifacts, ensuring the transparency and authenticity of digital records over time [8]. These emerging tools represent the next frontier of innovation in cultural preservation, providing new ways to protect and manage heritage in even the most precarious conditions.

[1] Syrian Heritage Initiatives of the Museum for Islamic Art/ Berlin State Museum https://syrian-heritage.org/.

### 1.3 Fostering Community Engagement for Sustainable Cultural Management

Involving local communities in the preservation process is a crucial component of sustainable cultural management. By actively engaging residents, cultural managers not only foster a sense of ownership and responsibility but also ensure that heritage assets are maintained and protected well beyond the initial recovery efforts. This local involvement creates meaningful bonds between the community and the preserved heritage, keeping it relevant and deeply connected to the evolving local identity. Empowering communities to take part in the conservation process strengthens long-term preservation efforts, reinforcing a shared responsibility for the protection of cultural legacies.

### 1.4 Collaboration Across Disciplines and Borders

Post-disaster cultural management also thrives on collaboration across multiple disciplines and stakeholders. Smart methodologies are most effective when supported by cross-institutional and cross-border partnerships, bringing together expertise from archaeology, history, conservation science, and emerging technologies. These collaborations enable the creation of comprehensive recovery plans that address both the immediate needs of heritage preservation and long-term sustainability [2, 3]. By integrating diverse perspectives, cultural managers can develop innovative strategies that enhance the resilience and future accessibility of cultural heritage.

## 2 Reproduction and Promotion of Cultural Memory

Digital technologies such as 3D scanning, printing, photogrammetry, and geographic information systems are invaluable in recording and preserving artifacts. These tools allow for the accurate capture of data, facilitating the reconstruction of damaged items and enabling remote access to information about the artifacts [9–11].

The concept of digital twins in the context of museum conservation involves creating a detailed virtual replica of museum artifacts that capture every detail of the original for monitoring, preserving, and studying purposes [12, 13]. These digital twins not only safeguard the objects but also enable 3D printing, allowing archaeologists to examine and analyze intricate details that might otherwise be lost.

The importance of documentation and preservation using all the modern tools and innovation available for conservators and archaeologists is crucial, particularly in high-conflict areas like Lebanon. The 2020 Beirut Port explosion, which led to the shattering of 72 glass objects at the AUB museum, emphasized the necessity for advanced conservation methods. The integration of these tools into the preservation efforts following the explosion has been crucial for ensuring that a detailed record remains for future generations, even if further damage occurs. The destruction highlighted the vulnerability of cultural heritage in regions prone to conflict, disasters, and political instability. The digital archiving of heritage objects can also serve as a safeguard against the total loss of cultural history, which can otherwise happen in the face of such catastrophes.

Following several conversations campaigns, a number of shattered glass objects were successfully restored. 3D models of these restored items were created using photogrammetry. This technique can be quite challenging with transparent materials such as glass due to their reflective and translucent nature. However, the iridescence of the glass, which can create surface reflections and color variations, helped reduce the transparency issue, making it easier to capture detailed images.

The objects were photographed using a turntable setup with coded targets and a stationary camera to capture multiple angles and overlapping images. Each object was photographed from one side at three different levels, then flipped, and the process was repeated for the other side. The photos were processed using Agisoft Metashape [14], a software that applies Structure from Motion (SfM) to generate 3D meshes out of pictures, effectively creating 3D digital reconstructions of the objects (Fig. 1). Additionally, we created physical replicas of the restored objects by 3D printing some examples in resin.

**Fig. 1.** 3D Model of a restored Glass Roman Bottle (inv. #4288).

## 3 AI-Driven Restoration and Conservation

After creating a digital replica of the reconstructed glassware (Fig. 2), we provide a visual guide to assist conservators during the reassembly process. A demo video is available at the following link: Glass Demo. This guide is built on the outcomes of the automatic reconstruction process, which consists of four main steps:

1. Training an object detection model.
2. Converting the file format to an ONNX format.
3. Running object detection inference in Unity.
4. Running the detection model inference on the HoloLens 2.

The first step involves compiling a dataset of images for each shard to train an object detection model. These images must include a variety of backgrounds and angles, ensuring that object detection works regardless of specific viewing perspectives or settings. The neural network used for this application is Tiny YOLOv4 [15] from DarkNet [16], mainly because it is the latest version compatible with Unity. The model is trained on either a GPU-powered computer or via Google Colab [17]. Once training is complete, the system generates a configuration file and a weights file.

**Fig. 2.** Left Glass Roman bottle before destruction, middle samples of fragments, right digital reconstructed results (inv. #4303)

Next, since these files cannot be directly used in Unity, the configuration and weights are converted into the Open Neural Network Exchange (ONNX) format [18], which Unity can process. ONNX consolidates these files into a single format while maintaining their accuracy and functionality. The conversion is carried out using a Python script designed to generate the ONNX file [19].

Unity's Barracuda package enables the ONNX files to be inferred, allowing certain neural network models to run within Unity. A GitHub repository [20] demonstrated how the Barracuda package can be used to run a YOLO model on a webcam feed, providing valuable insight into how a live webcam feed can be integrated into the ONNX model to generate bounding boxes in Unity. However, this solution produces only 2D bounding boxes, which are insufficient for head-mounted devices, as they require 3D inputs to interact with the environment.

Finally, another GitHub repository demonstrated how to use Barracuda to run a BlazeFace model that detects human faces with the HoloLens 2 [21]. The system detects faces from 2D images captured by the HoloLens 2's RGB camera and projects the bounding box coordinates onto a 3D mesh. This is achieved by casting a ray from the center of the bounding box along the camera's normal until it intersects with the 3D environment mesh. We adapted this 2D-to-3D projection script to identify objects detected by YOLO in the environment.

Given the HoloLens 2's limited processing power, running the YOLO model on every frame introduces performance bottlenecks. To resolve this issue, the script was modified to run only when the user pinches their fingers, processing a single frame at a time instead of doing it continuously. After each successful detection, a pin with a reference number is placed above the shard. The user is then prompted to start the reconstruction process, where a virtual representation of the base shard is displayed, guiding them to align it with the corresponding real shard. Once confirmed, the next virtual shard is shown, and the process repeats until all shards are reconstructed.

## 4 Long-Term Data Preservation

The digitization of cuneiform tablets at the AUB Museum serves as a critical case study addressing both the challenges and solutions in preserving digital records of tangible heritage at risk of deterioration. The use of digital tools for documenting and safeguarding cultural heritage is well-established, with ongoing research exploring best practices for digital documentation, integration of augmented and virtual reality, and advancements in software and techniques [4–6]. This digitization effort focuses on preserving the current state of fragile artifacts, which are invaluable due to their cultural and linguistic significance. The project specifically targets 69 clay tablets inscribed with cuneiform script, each featuring three-dimensional characters across all surfaces. These tablets provide crucial insights into the ancient world but are vulnerable to progressive degradation due to age. The urgency to preserve them, both physically and digitally, has led to innovative approaches in digital archiving.

At the start of the project, photogrammetry was employed, a common technique for creating 3D models. Initial attempts using a traditional setup—a camera mounted on a tripod and the tablet placed on a turntable—faced challenges due to the tablets' small size and uniform texture. Agisoft Metashape software [14] struggled to generate a complete 360-degree model. Although manual alignment of the tablet's sides was possible, this process was time-consuming and less accurate.

In search of a more effective solution, the team experimented with an iPhone 13 Pro, utilizing its macro camera feature to capture close-up, overlapping images. This approach was successful for some tablets, producing complete models with fewer photos. However, for tablets with inscriptions on only one side, the software again encountered difficulties in aligning images. Factors like the tablets' uniform shape and fragile condition prevented the application of physical markers, which could have facilitated better alignment. Subsequent tests involved Reality Composer, an iOS app using the iPhone Pro's built-in LiDAR scanner. This method proved faster, with a complete scan achieved in less than five minutes. While LiDAR scanning was quicker, photogrammetry produced higher quality models with better scale, highlighting the trade-off between speed and precision.

In parallel, the DITCH Incubator developed a comprehensive pipeline utilizing Structure from Motion, which processes multiple 2D images to reconstruct the object's 3D geometry. To optimize this process, custom-built turntables powered by Arduino-controlled servo motors were designed for both medium-sized and smaller artifacts. These turntables, were enclosed by wooden panels with black cloth to reduce ambient lighting interference, thereby allowing accurate, consistent rotations during image capture. Using an iPhone 13 Pro, the team captured images at 4-degree rotational increments, totaling 90 images per 360-degree rotation. The process was repeated from different camera angles, ensuring comprehensive coverage of the object. Images were imported into Agisoft Metashape for alignment, where manual intervention was occasionally needed to improve accuracy through the placement of markers on distinct points of the object.

Once aligned, a dense point cloud was generated, refined to exclude the turntable, and a mesh with high-resolution texture was applied. The final 3D model was exported as an.obj file, enabling further analysis, display, and archiving.

These obj files are to be shared with researchers worldwide, providing remote access to the digitized artifacts. Additionally, they can be 3D printed, either as enlarged replicas for better visibility of fine details or as 1:1 scale reproduction for educational and exhibition purposes (Fig. 3). This combination of digital preservation and physical reproduction ensures that the cuneiform tablets are not only protected from further deterioration but also made more accessible for study, enhancing both their academic and public value.

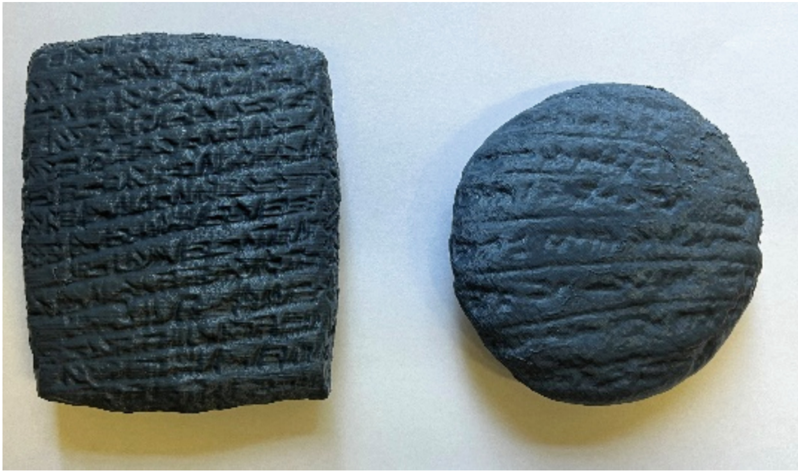

**Fig. 3.** 3D print in resin. Left inv. # 31.10 digitized using Agisoft. Right inv. # 34.104 digitized using Reality Composer.

The use of digital tools, such as photogrammetry and LiDAR scanning, has proven to be an invaluable approach in the preservation of cultural heritage artifacts like the cuneiform tablets housed at the AUB Museum. As these fragile objects continue to face deterioration, creating detailed digital replicas ensures that they remain accessible for future generations without risk of compromising their physical integrity. While the LiDAR method offers a faster and more streamlined scanning process, photogrammetry yields more accurate and detailed models, making it the preferred choice for preserving intricate artifacts. The ability to produce these high-quality digital archives not only safeguards these cultural treasures but also democratizes access, allowing scholars and researchers around the world to study these artifacts remotely. This dual approach of digital preservation and 3D reproduction is critical in preserving the legacy of the ancient world, ensuring both their physical and digital survival for years to come.

## 5 GIS Smart Technology Monitoring

The excavation of archaeological sites is a critical process for uncovering and safeguarding the remnants of past civilizations. Archaeologists have successfully recovered relics, structures, and other materials that offer valuable insights into the cultural heritage of ancient societies. Through careful study of these findings, researchers are able to reconstruct historical events, trace cultural developments, and protect fragile artifacts from further degradation.

In recent years, the 3D digitization of archaeological sites has emerged as a vital tool for preserving and documenting cultural heritage. This technology enables the creation of highly accurate digital replicas of entire excavation sites, allowing researchers to analyze and share these findings without the risk of further damage to the physical objects. Such digitization is especially crucial for sites that are susceptible to vandalism, natural disasters, or the inevitable effects of time.

To address these challenges to preservation, the DITCH Incubator has utilized a comprehensive pipeline that leverages 3D photogrammetry techniques, specifically utilizing the Structure from Motion (SfM) methodology, to generate digital twins of multiple archaeological sites in Lebanon. The pipeline begins with the use of high-quality image-capturing tools, such as smartphones or drones. For on-foot image capture, an iPhone 13 Pro is used, providing high levels of detail due to its maneuverability and mobility. For aerial image capture, a DJI Mavic 3 drone is employed, allowing for the documentation of large structures that are not easily accessible on foot, though this comes at the cost of reduced detail in favor of broader coverage. In cases where a site requires both detailed and expansive coverage, both tools are utilized to combine their respective strengths.

Once the surface of interest is captured using either device, the images are imported into Agisoft Metashape. The software aligns the images in 3D space by extracting features from each image and stitching them together. A sparse point cloud is generated from this alignment, which the user must then confirm. Upon confirmation, the sparse point cloud is refined into a dense cloud and further processed by the meshing algorithm to produce a textured 3D digital twin replica of the site.

For accurate scaling of the digital twin, the Mavic 3's onboard GPS system tags each image with its corresponding location. Agisoft Metashape uses these measurements to scale and localize the model. When only the iPhone is used for image capture, the scaling must be adjusted manually in the software. This is achieved by capturing a physical, scaled ruler in the environment and adjusting the digital twin until it matches the physical scale.

Anfeh, an archaeological site currently undergoing excavation, has yielded numerous significant discoveries, one of which is an oil press uncovered in 2022. Following its discovery, the DITCH Incubator applied the aforementioned pipeline to preserve the press. As the entire site was accessible by foot, only the iPhone was used for image capture. A 3D reconstruction of the oil press was successfully generated, which proved highly valuable after the site was damaged and vandalized, leaving the 3D replica as the only surviving record of the artifact (Fig. 4).

**Fig. 4.** 3D reconstruction of the discovered oil press at Anfeh

The Lebanese Mountain Trail (LMT) also contains numerous Roman sites and artifacts that have yet to be thoroughly analyzed and documented. The DITCH Incubator has successfully digitized more than nine sites along the trail, providing archaeologists with the ability to conduct their analyses on the digital reconstructions, eliminating the need for frequent physical visits to the site (Fig. 5).

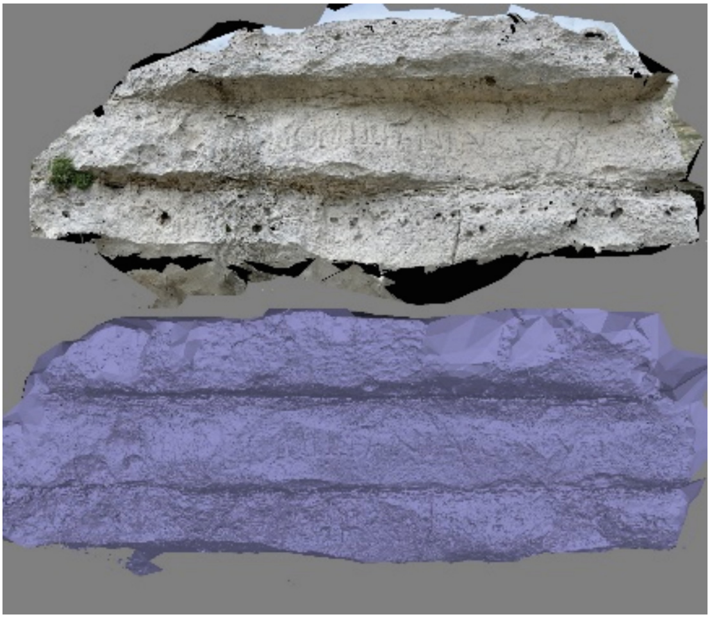

**Fig. 5.** Domitian inscription in Darjet Mar Semaan, Roman Road of Aaqoura, 3D reconstruction and "Shadow Layer"

## 6 Conclusion

The article details the critical role of digital heritage documentation and modern technologies in the protection, restoration, and rebuilding of tangible cultural heritage in areas affected by disasters and conflicts. Several examples demonstrated the applicability of digital technologies in this vein, from the 3D reconstruction using photogrammetry or small and large scale objects, to the digital guide used for the sake of renovating digital artifacts.

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# Restoration and Digitisation of the Tarxien Stone Bowl: A Multidisciplinary Approach

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**Abstract.** This paper presents an interdisciplinary effort involving the curatorial, conservation, and digitisation departments of Heritage Malta, focusing on the restoration and digitisation of a large stone bowl discovered in 1915 at the Tarxien Prehistoric Complex, a UNESCO World Heritage Site. Unearthed during excavations led by Temi Zammit, the stone bowl had been misassembled following its discovery, resulting in an inaccurate shape and structural vulnerability. By 2023, the bowl's degraded state necessitated a collaborative conservation project.

The curatorial team provided essential historical context and insights into the bowl's significance within the broader scope of Maltese prehistoric culture. In parallel, the conservation department oversaw the physical restoration, which required meticulous documentation and a sensitive approach to maintain the bowl's cultural integrity. The digitisation unit utilised advanced photogrammetry and 3D scanning techniques to virtually reconstruct the bowl and determine whether it could be returned to its original location in the prehistoric site.

This paper explores the historical importance of the Tarxien Prehistoric Complex, the curatorial perspectives on the artefact's significance, and the challenges encountered during the conservation process. The digitisation team's contribution is highlighted, showcasing how cutting-edge 3D technology can complement traditional conservation efforts to ensure the preservation and accurate representation of cultural heritage. Through this multi-disciplinary collaboration, the stone bowl was successfully restored and relocated to its original position, preserving its historical authenticity while demonstrating the future potential of integrated heritage preservation methodologies.

**Keywords:** Heritage Preservation · Interdisciplinary Collaboration · Digital Restoration · 3D digitisation

## 1 Historical Context of the Tarxien Stone Bowl

### 1.1 Discovery and Significance of the Tarxien Prehistoric Complex

In August 1915, during excavations led by the esteemed archaeologist Temi Zammit, the remains of a large stone bowl were discovered at the Tarxien Prehistoric Complex. This complex, one of several unique megalithic sites in Malta, is inscribed on the UNESCO


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World Heritage List for its outstanding representation of early human architecture and its significance to the Neolithic period, dating back to 3800 BC. The Tarxien site was first discovered in 1913 by Lorenzo Despott, a tenant farmer, who alerted Zammit after hitting large blocks of stone while ploughing his field in the area known as *Tal-Erwieħ*. Initial explorations yielded large stone blocks and fragments of prehistoric pottery, sparking a more comprehensive excavation two years later, where the true complexity of the site began to emerge.

The Tarxien Complex is particularly renowned for its well-preserved remains, which showcase intricate architectural designs unique to the Maltese Islands. This complex was built and used over several millennia, embodying the development of a sophisticated Neolithic culture that thrived in Malta. Among the notable finds within the site was the large stone bowl discovered next to an elaborately carved entrance. The basin, with a diameter of 1.4 m, was carved out of a single block of stone—a rarity for such a vessel, as most of the other large vessels found in the complex were made of ceramic. While the exact purpose of the basin remains speculative, its prominent placement and massive size suggest it played a key role in the rituals that occurred in the complex over 6,000 years ago (Fig. 1).


**Fig. 1.** Photographs dating 1915 to 1917 of the excavation and the first relocation of the Tarxien Basin. Dates: 1915–1917. Courtesy of Heritage Malta.

## 1.2 Curatorial Perspective: Early Restoration Efforts and Preservation Challenges

Following its discovery in 1915, the stone bowl, like many artefacts from the site, was shattered, with several fragments missing. The restoration of the basin began almost immediately, with its surviving pieces collected and reassembled. By 1916, photographs show the bowl reconstructed and placed in a chamber close to its original spot where it was found. However, no records from Zammit explain the rationale behind its relocation, although it is widely believed that concerns about the bowl's size and whether it would fit in its original location contributed to this decision. Instead, the conservators at the time chose a more accessible location for its restoration to allow enough space for the basin's reassembly.

By 1917, additional missing fragments were reproduced and attached to the original stone pieces in an effort to make the bowl whole once again. However, the restoration did not accurately reflect the original form of the vessel, as evidenced by the surviving fragments. Over the years, the basin suffered further damage, including an act of vandalism in 1925 that left the bowl broken once more. These repeated restoration attempts introduced various materials like cement and glues, which altered its structural integrity and shape, obscuring its original form.

In 2023, the curatorial team at the Tarxien site initiated a new project aimed at restoring the stone basin, addressing both the historical inaccuracies of previous restorations and the structural damage caused by age and repeated repairs. Curators, in collaboration with the Conservation Department and the Digitisation Unit of Heritage Malta, launched a multidisciplinary effort to explore the possibility of returning the bowl to its original location. Employing cutting-edge technology, including photogrammetry and 3D scanning, a virtual model of the bowl and its surroundings was created. This allowed researchers to test the basin's dimensions and assess whether it could be reassembled in its original location with greater accuracy than the previous attempts.

Through these modern techniques, the restoration project benefitted from historical expertise and advanced digitisation processes, merging curatorial knowledge with technological precision. The curatorial team's deep understanding of the basin's historical significance and their meticulous approach to preserving its authenticity have been vital in ensuring that this 6,000-year-old artefact is conserved with both cultural sensitivity and scientific rigor.

## 2 Conservation Interventions and Methodology

### 2.1 Introduction to Conservation Approach

The conservation of the globigerina limestone basin has been a recurring endeavour throughout the 20th century. Various interventions have been carried out, some of which were documented photographically. The basin, after being reassembled for the first time around 1916 and reconstructed a year later, underwent subsequent repairs, including reassembly in 1956–1959 after being documented as broken again in 1925. This sequence of interventions highlights the complexities faced by conservators over the years in preserving this artefact.

In early 2023, a curatorial decision was made to relocate the basin to its original position within Apse 9 of the Tarxien Prehistoric Complex.

However, due to the failing cement used to hold the basin together, it was deemed unsafe to simply move it. Instead, it was dismantled, treated, and reassembled in its original context, following ethical considerations and modern conservation methodologies (Fig. 2).

### 2.2 Condition Assessment

The basin, composed of 60 pieces held together by cement mortar, showed significant deterioration prior to the 2023 intervention. This condition assessment revealed vertical

**Fig. 2.** Conservators analysing digital map of 'unwrapped' model with a numerical system. Date: 2023. Courtesy of Heritage Malta.

cracks and instability, which had necessitated the use of a copper alloy wire to hold the basin together. The use of cement mortar, prevalent in the 1950s, had introduced various problems due to its incompatibility with the Globigerina Limestone. Cement, known to be a primary source of soluble salts, accelerated the limestone's deterioration, exacerbating erosion and delamination. Additionally, previous interventions involved filling gaps with small pieces of limestone and using various types of cement and adhesive substances, further complicating the conservation process.

### 2.3 Conservation Methodology

Although not directly related to 3D digitisation, challenges were encountered with multiple object entry numbers assigned to the same artefact within the national collection. Some artefacts had up to seven different identification numbers, stemming from historical initiatives and legacy systems. This situation caused confusion and complexity in managing and retrieving digital assets. Addressing this issue required a comprehensive review and consolidation of entry numbers to streamline the digitisation process and ensure accurate documentation.

1. **Photogrammetry and Preparation**

Before the basin's dismantling, photogrammetry was employed to confirm the feasibility of relocating the basin to Apse 9 and to calculate the required space. This also allowed for a thorough documentation of the basin's individual pieces, which were numbered and catalogued based on their position within the basin. The numbering system facilitated the reassembly process, ensuring that each piece would be placed in its correct orientation during the reassembly phase.

The megaliths in Apse 9, where the basin would be relocated, were conserved before work on the basin began. This step was crucial because, once the basin was in place, access to the megaliths would be severely restricted. Conservation treatments on the megaliths involved consolidation using an acrylic copolymer and pointing of cracks with lime-based mortars, ensuring long-term stability and compatibility with the basin.

2. **Dismantling and Cleaning**

Dismantling the basin began with the careful removal of the copper wire and the numbered pieces, starting from the rim and moving down in concentric circles. Cement and other materials from previous interventions were removed during this process, exposing original stone surfaces and providing insights into the methods used in past restorations.

Each piece underwent thorough cleaning, which included mechanical removal of cement and soiling using scalpels, brushes, and deionised water. In some cases, pre-consolidation was necessary to strengthen weakened areas of the stone before further cleaning could be performed. A biocide was applied to eliminate biological growth, which had manifested as black biofilm and patches of lichen, particularly on the exterior and interior surfaces of the basin.

3. **Reassembly**

Once cleaning and consolidation were complete, the reassembly process began. Each piece was reattached based on the photogrammetry scans and numbered system. Reassembly commenced with the base pieces, which were secured using fibre glass rods inserted into drilled holes. These rods provided structural support, ensuring the basin's stability once fully reconstructed.

Lime-based mortars, both coarse and fine, were employed to fill gaps between the pieces, ensuring that the final appearance was as cohesive as possible. In areas with larger voids, small pieces of Globigerina Limestone were used as infill, secured with epoxy resin and finished with the same lime-based mortars. This approach ensured that the material used was compatible with the original stone while maintaining the basin's structural integrity (Fig. 3).

## 2.4 Ethical and Practical Considerations

The conservators faced numerous challenges, both ethical and practical, throughout the project. Decisions regarding the extent of cleaning, the use of modern materials, and the overall aesthetic of the reassembled basin had to balance historical accuracy with the long-term preservation of the artefact.

Working in collaboration with the curatorial and digitisation departments, the conservation team adhered to ethical guidelines as outlined by the ICOM-CC, ensuring that all interventions were reversible and well-documented. The project also followed conservation best practices by incorporating non-invasive methods, such as photogrammetry, to minimize handling of the artefact and avoid potential damage.

**Fig. 3.** Photographs showing the reassembly of the Tarxien Basin. Date: 2023. Courtesy of Heritage Malta.

### 2.5 Challenges and Conclusion

The greatest challenge encountered during the conservation process was working in extreme summer heat, which often necessitated pauses in the work schedule to protect both the conservators and the artefact. The tight workspace around Apse 9 also presented difficulties, particularly when it came to reassembling the basin in close proximity to the megaliths. However, despite these challenges, the project was successfully completed, preserving the basin for future generations and restoring it to its original location within the archaeological site.

The interdisciplinary collaboration between the conservators, curators, and digitisation experts played a key role in the project's success. By combining traditional conservation techniques with modern technologies, such as 3D scanning and photogrammetry, the team was able to overcome the challenges posed by this complex restoration effort. The result is a carefully reassembled basin that preserves both its historical significance and its structural integrity.

## 3 Digitisation Process of the Stone Basin

### 3.1 Initial Scanning and 3D Model Overlay

The digitisation process began with a pivotal scanning session aimed at determining the feasibility of relocating the stone basin to its original position. This required the creation of two key 3D scans: one of the stone basin itself and the other of its original location within the site. The initial objective was to digitally overlay the basin onto its historical placement to assess whether it could physically fit.

For the site scan, photogrammetry was chosen as the primary methodology. This technique was augmented with printed targets to ensure that the 3D model scale was accurate. However, when scanning the stone basin, a handheld laser scanner was initially used but faced difficulties due to the basin's size. As a result, photogrammetry was once again selected for capturing the basin, ensuring consistency across the models.

The captured data from both scans were processed to generate detailed 3D models. Cleaning the models involved removing non-essential elements and separating the basin from the surrounding floor. The stone basin was then superimposed onto the virtual model of the site, confirming that it could be reassembled in its original spot. This phase not only set the stage for further digitisation but also provided the first evidence that physical restoration could proceed (Fig. 4).

**Fig. 4.** First virtual relocation showing that the artefact would fit in its original location. Date: 2023. Courtesy of Heritage Malta.

### 3.2 Establishing a Numerical System for Interdepartmental Coordination

Once it was confirmed that the stone basin could be relocated, the conservators planned for its disassembly, and the digitisation team developed a numerical system to ensure clarity between departments. Using the 3D model, each individual part of the basin was assigned a numerical label directly onto the textured surfaces. These labels were subsequently "unwrapped" onto a flat surface, which allowed for a printed reference sheet to guide the disassembly and reassembly process.

In addition, the virtual 3D model with its numerical labels was shared with the conservation team. This proved to be a highly effective means of coordinating the physical disassembly of the stone basin, ensuring that every part could be tracked and reassembled accurately. The collaborative effort between the conservators and the digitisation team was vital for maintaining the integrity of the artefact throughout the process.

### 3.3 Scanning of Individual Parts

After the basin was disassembled into approximately 60 individual parts, the next phase involved scanning each part separately. This approach was critical for two reasons:

1. **Comprehensive Documentation**: This marked the first instance of the basin being fully documented in 3D, capturing details from all angles, including areas previously obscured.

2. **Revealing Restoration Practices**: The scans exposed the significant use of cement during the initial restoration, providing valuable insights for the ongoing conservation effort.

To facilitate this, a handheld laser scanner was used, supported by physical 3D targets for positioning. The smaller size of the individual parts allowed for detailed scanning from multiple angles, and each part was digitally merged into a unified 3D mesh. Given the focus on structure and volume rather than visual texture, texture data was intentionally omitted, streamlining the processing of all 60 parts.

### 3.4 Virtual Assembly and Negative Space Analysis

With all parts scanned, the team proceeded with the virtual assembly of the stone basin. This process served two major research purposes:

1. **Negative Space Analysis:** By comparing the original scan with the virtually reassembled version, the team could identify gaps where cement had been applied during previous restoration efforts.
2. **Infographic Development:** The final 3D model allowed for the creation of detailed infographics, which were later used to guide conservators in the physical reassembly.

The virtual assembly relied on complex geometric algorithms to align the surfaces of each part with those from the original scan. Initially, three key reference points were selected to align identical positions on both surfaces, allowing the complex geometric algorithms to complete the assembly. The process began with larger components and progressed to smaller ones. Once completed, the final 3D model provided an eight-view perspective of the basin, giving conservators a complete visual reference from all angles.

### 3.5 Physical Placements for Virtual Models

After confirming the virtual assembly, the digitisation team turned its attention to the physical relocation of the basin, collaborating closely with the restoration team. Given the size and physical restrictions of the new location, the virtual data needed to be translated precisely to the physical site.

Architectural modelling software was employed to extract precise measurements from the 3D model. By using triangulation techniques based on fixed points both in the model and on the site, the team identified accurate positions for each part. The alignment of the three primary base components of the basin was pivotal to ensuring the entire structure could be reassembled in the exact location as intended (Fig. 5).

### 3.6 Assumptions and Limitations in the Digitisation Process

Throughout the digitisation process, certain assumptions were made based on the practicalities of working with both the virtual and physical forms of the stone basin. These assumptions include:

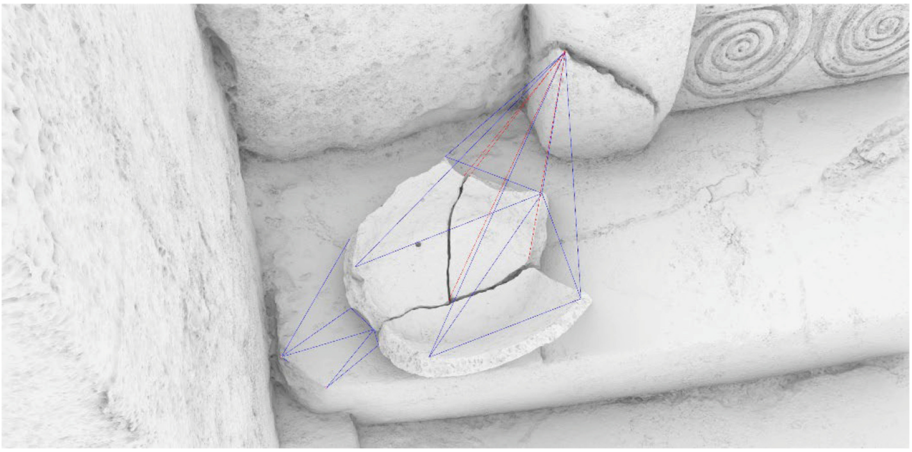

**Fig. 5.** Digital render showing triangulation techniques based on fixed points both in the model and on the site. Date: 2023. Courtesy of Heritage Malta.

- **Volume Assumptions:** It was assumed that the stone basin's volume would remain constant or even decrease post-disassembly and reassembly due to the planned reduction in cement use.
- **Reassembly Sequence:** It was presumed that the components would be reassembled in the exact order they were disassembled, which, while ideal, posed challenges due to the complex nature of physical reassembly.
- **Alignment Limitations:** Despite the advanced capabilities of geometric algorithms, the alignment process had limitations, particularly in distinguishing between surfaces altered by cement and the original stone.

In conclusion, the digitisation process was crucial for the restoration and conservation of the stone basin, and it was instrumental in providing an accurate framework for both the virtual and physical reassembly. While certain limitations were encountered, the use of cutting-edge 3D technologies and a multi-disciplinary approach ensured the project's overall success.

# 4 Conclusion and Future Applications - The Role of the Digital Memory Twin

## 4.1 Reflections on the Restoration and Digitisation Efforts

The digitisation process, supported by rigorous conservation techniques, successfully addressed the two main goals of the project: the virtual reassembly of the stone basin and the physical relocation of its components. The digital reconstruction necessitated precise planning and collaboration between departments. It also provided a scalable model that conservators could rely on throughout the physical restoration. The complexities of reassembling an artefact of this size, with its history of earlier restorations, necessitated the use of cutting-edge 3D digitisation tools such as photogrammetry, hand-held laser scanning, and complex geometric algorithms for surface alignment.

The project also demonstrates the importance of interdisciplinary collaboration between conservation, curatorial, and digitisation teams. Each phase—whether creating the numerical system for disassembly, scanning individual parts, or executing the virtual and physical reassembly—required careful coordination, documentation and data sharing. Comprehensive paradata collection is essential in the scanning process, as it meticulously documents the exact techniques, conditions, equipment, and software used in scanning and post-processing. This critical information provides future generations with a detailed understanding of the work conducted, ensuring long-term preservation and context for digitized assets.

This multi-layered approach set a new benchmark for future digitisation, curatorial and conservation initiatives at Heritage Malta.

### 4.2 The Digital Memory Twin

One of the most significant outcomes of this project is the creation of a Digital Memory Twin of the stone basin. A digital memory twin is a highly detailed, digital representation of a physical cultural heritage asset that captures not only its physical features but also its historical, contextual, and interpretive data. This concept goes beyond traditional digital models by incorporating rich metadata, paradata, and archival information, creating a "twin" of the object that preserves its cultural memory. Memory twins are designed to evolve over time, integrating new information and insights, allowing future generations to understand, study, and interact with heritage assets as if accessing a virtual, time-traveling version of the original.

In this case, the Memory Twin goes beyond a simple 3D model. It serves multiple purposes:

- **Preservation of Knowledge:** Preserving the basin involves not only maintaining its physical state but also capturing detailed information about its original materials, historical repairs, and broader cultural significance. Documenting these materials is critical, as it provides insights into the basin's craftsmanship, preservation techniques, and the environmental factors influencing its degradation. This recorded knowledge serves future conservation efforts by offering a comprehensive understanding of the object's composition and history, ensuring that its authenticity and historical integrity are maintained over time.
- **Research and Education:** By creating a highly detailed, textured 3D model of the basin, this digital tool can serve as a valuable outreach resource for educational purposes. Scholars, researchers, and students can closely examine every aspect of the artifact at any time, reducing the need for physical access and thus minimizing wear on the original object. Schools, universities, and heritage institutions globally can integrate the model into digital learning platforms and even create precise replicas through 3D printing, fostering interactive and immersive learning experiences.
- **Conservation Monitoring:** Acting as a baseline for future conservation work. Any new restoration efforts can be documented and compared against this digital version, enabling more precise monitoring of the artefact's condition over time.
- **Public Engagement and Accessibility:** Reusing 3D cultural heritage assets through virtual tours and digital exhibitions allows the public to engage with significant

artifacts like the stone basin from anywhere. This approach enhances accessibility, enabling broader public interaction and participation, while promoting cultural appreciation by bringing detailed, high-fidelity models to global audiences across diverse platforms.

In terms of its broader impact, the Memory Twin reflects a growing trend in cultural heritage digitisation, where artefacts are not only preserved for posterity but also serve as evolving records that adapt to new conservation technologies, historical research, and curatorial needs.

### 4.3 Future Applications and Challenges

The use of 3D digitization in cultural heritage is rapidly evolving, offering innovative ways to interpret and engage with historical artefacts. As threats like climate change and environmental degradation put heritage sites at risk, institutions such as Heritage Malta are turning to Digital Memory Twins as a key strategy for preserving the memory and significance of cultural objects. Beyond preservation, these digital replicas provide opportunities for reinterpreting artefacts and reaching new audiences through more immersive and interactive experiences. By leveraging 3D technology, museums and cultural sites can offer enhanced visitor engagement, making heritage more accessible and appealing to diverse groups.

However, with these advancements come several challenges. Managing the vast amounts of data generated by digitized artefacts requires robust systems for long-term storage and preservation. Ethical considerations must also be addressed, ensuring that any manipulation of digital models remains true to the original artefact, with transparency around any changes made for conservation or public engagement. Additionally, technological advancements mean that digital models must be regularly updated or converted to ensure future compatibility and usability. As the field evolves, it is essential to strike a balance between innovation and responsibility, ensuring that digital heritage serves both preservation and dynamic visitor engagement needs.

### 4.4 Shaping the Future of Heritage Preservation

The digitisation and restoration of the stone basin from Hal Tarxien have set a precedent for the future of cultural heritage projects. The success of this project, bolstered by interdisciplinary collaboration and advanced 3D technology, highlights the potential of digital tools in both conserving and disseminating knowledge about invaluable historical artefacts. The creation of the Memory Twin opens new doors for research, education, and public engagement, ensuring that cultural heritage remains accessible and relevant in the digital age.

As Heritage Malta continues to explore the use of digitisation in its projects, the lessons learned from this initiative will undoubtedly influence future conservation efforts, helping to safeguard not only the artefacts of the past but also the cultural memories that define them for generations to come.

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