Project CHANGES - Spoke 5

D5.2 – Report on digital tools for data sharing and processing, designed to support CH stakeholders in the management and analysis of diagnostic results – v1.0

Deliverable information

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No.	Name of Partner	Acronym	Role
1	Consiglio Nazionale delle Ricerche	CNR	Spoke leader
2	Opificio delle Pietre Dure	OPD	Spoke co-leader
3	Sapienza Università di Roma	UNIRM1	Member
4	Università degli Studi di Napoli Federico II	UNINA	Member
5	Alma Mater Studiorum – Università di Bologna	UNIBO	Member
6	Università degli Studi di Catania	UNICT	Member
7	Università degli Studi di Firenze	UNIFI	Member
8	Gran Sasso Science Institute	GSSI	Member
9	EDIL CO. S.r.l.	EdilCo	Member

Executive Summary

This report is part of the work performed in the project PNRR PE 5 "CHANGES", and specifically in Spoke 5 "Science and Technologies for Sustainable Diagnostics for Cultural Heritage", WP5 "Digital technologies, AI/ML solutions, chemometric methods supporting data-driven Heritage".

It presents and discusses the results obtained in the project, planned as: *R5.2 – Design of digital tools for data sharing and processing, designed to support CH stakeholders in the management and analysis of diagnostic results* and constitutes one of the Deliverables produced: *D5.2 – Report on digital tools for data sharing and processing, designed to support CH stakeholders in the management and analysis of diagnostic results*.

The work done is congruent with the analysis of the user needs, which have been previously assessed following the opinions and desiderata of the stakeholders (see report *D5.1 – Report on data encoding / integration / processing needs of CH stakeholders*).

The scope of this report is to present and discuss the activities performed in WP5 by the research partners involved. Following the results of the survey of our community of practitioners and experts, we focused our activity on: implementing services for data analysis; designing interactive and collaborative visualization tools, including features for the integration of sample data and interactive inspection; and devising digital methodologies for the restoration of missing parts. Thus, those experiences have considered different aspects of the required digital support to scientific investigation and presentation of CH assets. The experiences reported contribute to the needs of supporting the knowledge consolidation process with digital instruments, leading to the common goal of a better comprehension and assessment of the conservation conditions of heritage assets.

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1. Introduction

The Cultural Heritage (CH) community (museum curators, conservators, restorers, art historians, ...) requires solid digital support to enable CH workflows based on cooperative activities, where resources and results are accessible and easily shared and, finally, data are permanently archived. This requires common and interoperative digital data types, common digitization processes, and digital platforms/tools supporting the work of stakeholders in all phases of their activities.

WP5 aims at developing innovative digital technologies to support data-driven research in the CH domain, enabling a new paradigm for data collection, integration, processing, visualization, annotation, and documentation. In the first phase of the project (Y1) we ran a survey to investigate CH stakeholders' needs and gather structured information on current and future practices in digital CH, thus following a user-driven approach.

The survey demonstrated the community involvement and commitment towards the adoption of digital technologies and tools; as an example: the great majority of the institutions are investing their funds in digitization (85%), are willing to invest time and personnel resources in data semantic enrichment (83%), and would also be willing to be monitored while using the new tools provided by the project (83%). The survey showed a community very well-oriented towards digital CH, used to work with digital data (even in 3D format) and already aware of the best practices regarding data management (archival, preservation, access), and with some previous experience in the production of dissemination content (often as a by-product of investigation projects).

New digital tools should be primarily focused on implementing services for data analysis, since almost 50% of respondents admit they are not using or planning to use data analysis software. From this, it follows that there is wide space for improvement in the adoption and use of data analysis services. In this regard, the survey had an impact in steering the design effort of WP5, providing a list of priorities regarding the features that the developed tools should support (interactive visualization and data inspection tools, before others) and other interesting insights (e.g., the fact that semantic data ingestions, still considered important, just follow interfaces usability among respondents).

The CH context is very broad, both in terms of preservation goals and subjects (ranging from a small artifact to an entire building, up to an archaeological site or an entire city) and in terms of research/conservation questions (which, in turn, often require different representation approaches, media, scales, and accuracies). The work planned in WP5 could not be omni-comprehensive; we had to select some activities and specific needs to focus our concrete work on a small set of objectives which could be reached in this project's duration. Therefore, we report here the results obtained on those research lines, each one corresponding to a specific research question:

- Acquisition of knowledge - Scientific diagnostic analysis is a mandatory phase in any study concerning a heritage asset. Multiple technologies allow us to produce solid evidence on the constituent materials, the production process, and the conservation conditions. Many of those diagnostic technologies produce a very dense set of data (often in the form of false color images) which require analysis and study to better comprehend the knowledge encoded. Instead of being cumbersome and very slow when demanded by a human operator, this analysis phase can become more efficient and precise by introducing automation and Artificial Intelligence (AI) approaches. The first experience presented in this section presents and discusses the results obtained by introducing AI processing to perform improved spectral analysis over raw data returned by MA-XRF applied to paintings.

- Restoration – Artwork or findings restoration is an activity following the first phase of characterization and comprehension of the finding's structure and conservation conditions. Restoration could focus on the surface of the artwork, stopping the deterioration process (this is the usual case of paintings or frescoes), or can also focus on the study of the original shape, working either to the recombination problem (finding recomposed by fragments) or the remodeling of missing parts. The latter is the focus of the second experience reported in the following section. Modern digital 3D fabrication technologies allow nowadays to study, rehearsal and produce replicas of missing parts, going beyond what was done just manually in the past. 3D modelling solutions allow to produce quite easily multiple reconstruction hypothesis, which can be assessed and evaluated in the digital realm, and then could be produced as physical replicas with cheap 3D printing devices. Subsection 2.2 presents an experience focusing on the integrative restoration of archaeological remains (mostly bones and dental findings) by using reverse engineering techniques and rapid prototyping.
- Monitoring of conservation conditions - The analysis of conservation conditions of material assets (namely, the case of architecture is a major focus for these approaches) requires the installation of several sensors, sampling different physical parameters, either outdoor or indoor and for a given time span. All the data produced by those sensors (usually IoT devices) must be collected, possibly in real-time, stored, and studied. Therefore, efficient software solutions are needed for gathering and visualizing the data remotely

to support the analysis of the conservation staff. Subsection 2.3 presents an experience run in the historical center of L'Aquila.

- **Data fusion and presentation for collaborative studies** – When a CH object or site is being studied, the diagnostic data produced often need to be spatially arranged to be presented in an accessible and intuitive way, for example to the team of experts collaborating in a specific knowledge or conservation project. **3D data** are an excellent medium to provide spatial essence and can act as a pivot for organizing analytical datasets, enabling visual analysis, which is a major part of our understanding process. When collaborative teams are spread across multiple locations, enabling remote access to visual analytics is almost mandatory. To this end, using web-based visualization tools to present data is a really good option. Subsection 2.4 presents two 3D-based resources aimed at integrating and visualizing different diagnostic data. Developed as dedicated **web-based visualization systems**, these tools allow **data from elemental analysis and from autonomous microclimate monitoring systems** to be **interactively mapped to the respective sampling locations/areas in their reference 3D digital model,** and to **visually present them to the users in real time**. To define, and at the same time test these resources, two different case studies have been implemented: the first experience designed to assess the hygrometric and thermodynamics conditions of the Art Gallery of the Civic Museum Castello Ursino in Catania, and the second one to study the characterization of the mortars of Palazzo Biscari, one of the most important eighteenth-century private palazzi in Catania.

2. Experiences and results

2.1 AI-Powered digital tools for analysis and diagnostics

2.1.1 Deep learning for enhanced spectral analysis of MA-XRF datasets of paintings

The ISPC-CT activity in WP5 introduces a deep learning-based approach for rapid and quantitative analysis of MA-XRF datasets composed of millions of XRF spectra, addressing the analytical challenges posed by these complex and voluminous datasets generated by macro x-ray fluorescence (MA-XRF), a well-established tool in the domain of noninvasive imaging techniques applied for the study and conservation of paintings in WP1 and WP2 of the SPOKE 5 of CHANGES. To address the complexity of MA-XRF data, we have incorporated machine learning strategies specifically designed for the analysis as they allow for identification of nontrivial dependencies and classification within these high-dimensional data, thereby promising comprehensive interrogation. Our approach overcomes the limitations of traditional deconvolution methods that require specialized expertise. We introduce a deep learning algorithm trained exclusively on synthetic spectra generated via Monte Carlo simulations with multi-layer pictorial stratigraphy models and variable pigment compositions. The architecture employs a 1D convolutional network without normalizations or dropout, optimized for spectral analysis tasks. The synthetic dataset is generated using XMI-MSIM software based on MC simulations with a fundamental parameters approach tuned for our MA-XRF setup geometry and x-ray source. We model paintings using a five-layer structure: gypsum support, preparation layer (white lead pigment mixed with linseed oil, 60µm thick), pictorial layer (mixture of pigments and binder with 1:1 volume ratio), varnish layer, and air path. Pigments are randomly chosen from 57 historical and modern compounds, with layer composition following a Poisson distribution and thickness ranging from 1 to 120µm. We generated 500,000 random spectra to ensure a comprehensive representation of typical painting scenarios.

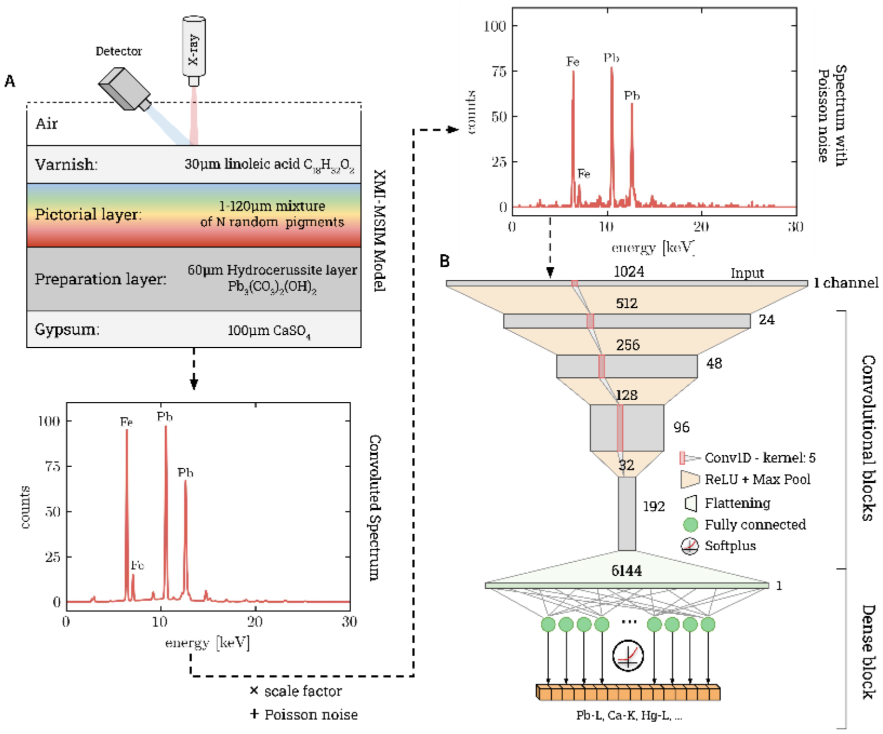

Fig. 1 (A) Schematics of the pictorial model used in the MC simulation to generate the synthetic XRF spectra for training the network. (B) Schematics of the neural network used here. We divide the network into two parts: the convolutional blocks and the dense block. The dense block is kept fixed in the first part of training and is enabled only after the convolutional blocks are trained. ReLU, rectified linear unit.

The CNN-based model is trained to infer net counts per emission fluorescence line in XRF spectra. Considering that measured counts are affected by Poisson noise, we avoid normalization, batch normalization, and dropout, with all biases disabled to preserve absolute count information. Training occurs in two stages: initially, dense layers are partially disabled while the network learns peak shapes, then full training proceeds after convolutional layers are established. We introduce on-the-fly scale changes respecting Poisson noise, rescaling convoluted spectra before applying noise during training. This approach increases dataset diversity as no spectrum is fully repeated, reducing overfitting. We applied our methodology to two Raphael paintings at the Museo di Capodimonte (Naples): "God the Father" (110×73 cm wood panel) and "Virgin Mary" (51×41 cm wood panel), representing fragments of a grand altarpiece painted in 1500–1501. MA-XRF data were recorded with different lateral resolutions from millimetric to micrometric scales.

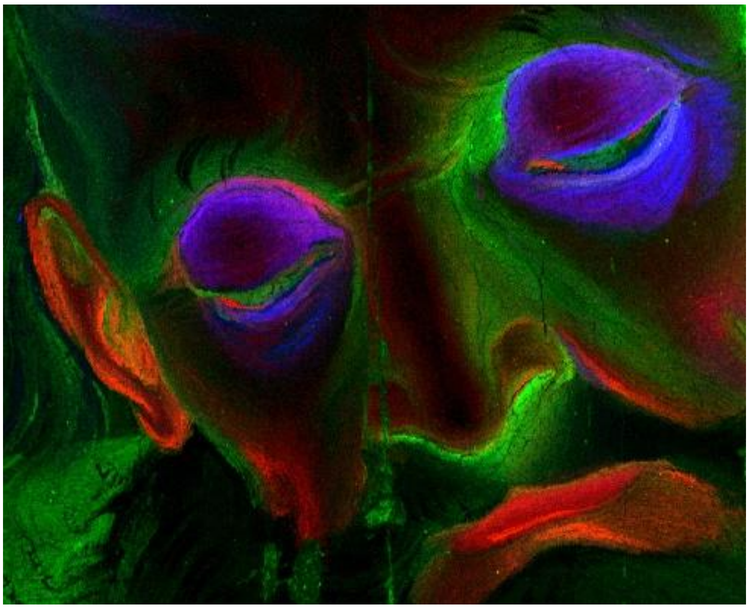

Fig. 2 Composed Red-Green-Blue (RGB) image of the elemental distribution maps of Hg-L, Fe-K, and Cu-K. The image provides insight into the painting technique of Raphael.

Results demonstrate superior accuracy in quantifying fluorescence line intensities while effectively eliminating artifacts typical of conventional analysis methods. Most notable improvements occur in low signal-to-noise scenarios, where traditional deconvolution tends to overestimate counts, including when elements are absent. The network can separate the contributions of elements more precisely, hence providing an improved estimate of counts. The developed method offers a fast, robust, and generalizable alternative for pictorial work analysis, enabling accurate MA-XRF map creation without manual intervention and potential extension to different experimental setups and stratigraphies. Success is founded on existing knowledge of x-ray generation and matter interactions, combined with advanced simulation software capable of generating synthetic spectra that closely emulate experimental instruments.

2.1.2 Digital tools for robotics diagnostics

The ISPC-CT unit has developed, within WP5, an interactive digital platform that drives the robotic spectrometers produced in WP1 of SPOKE 5 for the investigation of artworks. More specifically, ISPC-CT designed and built in WP1 an innovative XRF/IR spectrometer mounted on a collaborative robotic arm, specifically engineered for the non-invasive scanning and analysis of complex three-dimensional cultural-heritage objects. The digital platform allows operators to define measurement areas and acquisition parameters for the spectrometric head, while the robot dynamically adjusts its pose to maintain an optimal geometry on curved or irregular surfaces. This capability guarantees consistent, high-quality elemental mapping across sculptures, reliefs and other 3D artefacts. A critical aspect is the creation of accurate 3D models of measured objects, which serve as the foundation for measurement planning and trajectory generation. The developed application processes measured point clouds, generating mesh-based 3D models that provide essential geometric information for robotic path planning and enable precise visualization of measurement areas. The developed application provides an intuitive interface for measurement planning and execution. In particular: 1) The software processes 3D surface data from the generated models to identify measurable areas and automatically generates measurement trajectories that follow the object's topology while maintaining consistent standoff distances. 2) Advanced algorithms calculate optimal measurement paths that avoid collisions between the robotic arm, XRF/IR scanner, and the artifact. The system accounts for the robotic arm's kinematic constraints and workspace limitations while preventing any contact with the cultural heritage object. Users can interactively define relevant measurement parameters through a graphical interface that visualizes the proposed measurement trajectories overlaid on the 3D object representation. The system maintains precise control of measurement distances, ensuring consistent data quality while protecting delicate surfaces.

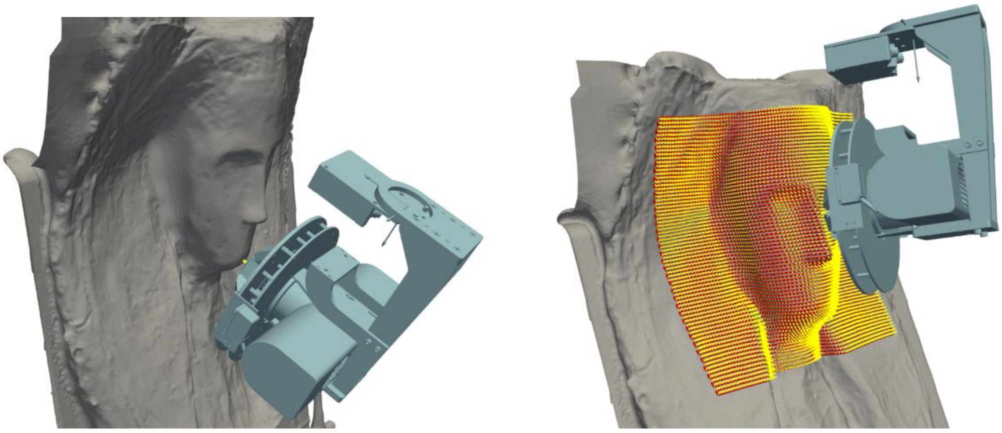

Fig. 3 Measurement trajectories avoiding overlaps for the measurement of the XRF/IR scans of 3D objects.

2.2 Methodology for the integrative restoration of archaeological remains by using reverse engineering techniques and rapid prototyping

UNIBO contribution to WP5 focuses on the virtual restoration of bone and dental finds involved in invasive sampling related to physicochemical and biomolecular analyses. It is a High-accuracy methodology for the integrative restoration of archaeological teeth and bones that uses reverse engineering techniques and rapid prototyping. The reconstruction of the original morphology of bones and teeth after sampling for physicochemical (e.g., radiocarbon and uranium series dating, stable isotope analysis, paleohistology, trace element analysis) and biomolecular analyses (e.g., ancient DNA, paleoproteomics) is appropriate in many contexts and compulsory when dealing with fossil human remains. We used computed microtomography (microCT), reverse engineering (RE), computer-aided design (CAD), and rapid prototyping (RP) techniques to fabricate customized missing parts. It is a composite procedure consisting of: a) the microCT scanning of the original specimens; b) sampling; c) the microCT scanning of the specimens after sampling; d) the reconstruction of the digital 3D surfaces of the specimens before and after sampling; e) the creation of digital models of the missing/sampled portions by subtracting the 3D images of the preserved portions (after the sampling) from the images of the intact specimens (before the sampling) by using reverse engineering techniques; f) the prototyping of the missing/sampled portions to be integrated; g) the painting and application of the prototypes through the use of compatible and reversible adhesives.

This methodology has been refined over the past few months and tested on two main case studies concerning two Paleolithic contexts, which involved the restoration of two human remains. Several related scientific publications have been published, presented, or are currently in progress [TCR25], [PRV25a] [PRV25b], [PRV25c].

2.2.1 Introduction

In paleoanthropological research, dental and osteological remains are an irreplaceable source of information about the life history of an individual and the community to which it belonged.

In recent years, the application of physicochemical (e.g., radiocarbon and uranium, stable isotope analysis, paleohistology, trace element analysis) and biomolecular analyses (e.g., ancient DNA, paleoproteomics) have revolutionized the field of osteoarchaeology and paleoanthropology.

Even though they involve, in most cases, destructive or micro-destructive analyses, their application has become fundamental in the bioarchaeological field, allowing the retrieval of information that is not accessible through the employment of other non-destructive methodologies [BPOP21], [LCTTB18], [LDV19], [NLR20], [SMV18], [SBL18].

Therefore, standard protocols are needed to plan integrative restoration before the samples are even collected and need to consider the state of preservation of the specimens (size and morphology, as well as physicochemical properties) and their possible use after restoration (e.g., further scientific research, exhibition, teaching).

Traditionally, the reconstruction requires a manual approach, which is strongly influenced by the experience and subjectivity of the operator, is highly invasive, and becomes more demanding the more severely damaged and morphologically complex is the region to be reconstructed.

So far, the replacement of missing parts has involved the reproduction of the external integrity of the specimen either by applying dental wax or hot paste made of organic and inorganic components (modelling chalk, raw beeswax, resin, zinc white) or by using mold-based techniques for contact replication of the missing parts, as a means to facilitate future interpretations of the element [C08], [CCSP09].

In the past decades, high-resolution 2D and 3D imaging technologies have generated a considerable degree of interest for several applications. Examples of the fields of application are paleoanthropology, archaeology, geology, civil engineering, archaeology, reverse engineering, medicine, and virtual reality [HVSRBCBOB20], [STD09], [TFVGF16], [VST18]. This has led to a remarkable development of virtual restoration methodologies with reverse engineering (RE) techniques [CVSBSSL21], [HMVBR19], [SCWB13], to the increasingly widespread use of rapid prototyping (RP) to create replicas and scale reproductions of movable and immovable objects [DTEW00], [PTDC04], [TB12], [UZVAD18], or, in rare cases, to the manufacture of missing parts that are useful for restoration [FDPBG08].

A virtual anthropological approach [BBSW11], [BGSH14], [ROB20], [SCWB13], [W14], [WB11], [ZP05], based on reverse engineering, computer-aided design (CAD) and rapid prototyping technologies can facilitate and improve these operations because they minimize the subjective choices of the operator and increase the reliability of the result.

At present, the virtual reconstruction and rapid prototyping of missing parts are mainly used in maxillofacial surgery, where the design of customized implants using CT-derived 3D models, combined with the development of new biocompatible materials and rapid prototyping technologies, has led to multiple advantages over traditional surgical techniques [API19], [CLA20], [GGMMBT21], [MDO21], [SRYVK18], [TKSRM19], [ZSHBLLZ10].

Our work led us to provide clear guidelines for the reconstruction of osteoarchaeological material by combining traditional methods and tools developed in manufacturing industries (reverse engineering, 3D modeling, rapid prototyping), as well as in the field of medicine and research (e.g., computed tomography (CT) and computed microtomography (microCT)). This innovative approach overcomes the limits of manual procedures by: a) strongly reducing the handling of the specimen, ultimately reducing risks of damage; b) exploring alternative solutions for both digital and physical reconstructions; c) printing copies of the final product that can be used for, e.g., scientific purposes, exhibition, educational or promotional activities.

2.2.2 Materials and methods

Our experiment of integrative restoration aimed at restoring the original morphology of osteological finds was carried out on two human teeth from Upper Paleolithic contexts that were sampled for physicochemical and molecular analyses.

Case study 1: Physical restoration after sampling of the human phalanx from Obłazowa Cave, Early Upper Paleolithic site at, Poland. At present, it is the oldest *Homo sapiens* remain in Poland.

Case study 2: Physical restoration after sampling of the human tooth from Observatoire Cave, Paleolithic site in the Principality of Monaco (MC). At present, it is the oldest *Homo sapiens* remain in the entire Principality of Monaco.

The here-described protocol for physical restoration involved various stages: a) microCT of the original specimens; b) sampling; c) microCT of the specimens after sampling; d) reconstruction of the digital 3D surfaces of the specimens before and after sampling; e) creation of digital models of the missing/sampled portions by subtracting the 3D images of the preserved portions (after the sampling) from the images of the intact specimens (before the sampling) by using reverse engineering techniques; f) prototyping of the missing/sampled portions to be integrated; g) painting and application of the prototypes using compatible and reversible adhesives (Fig. 4).

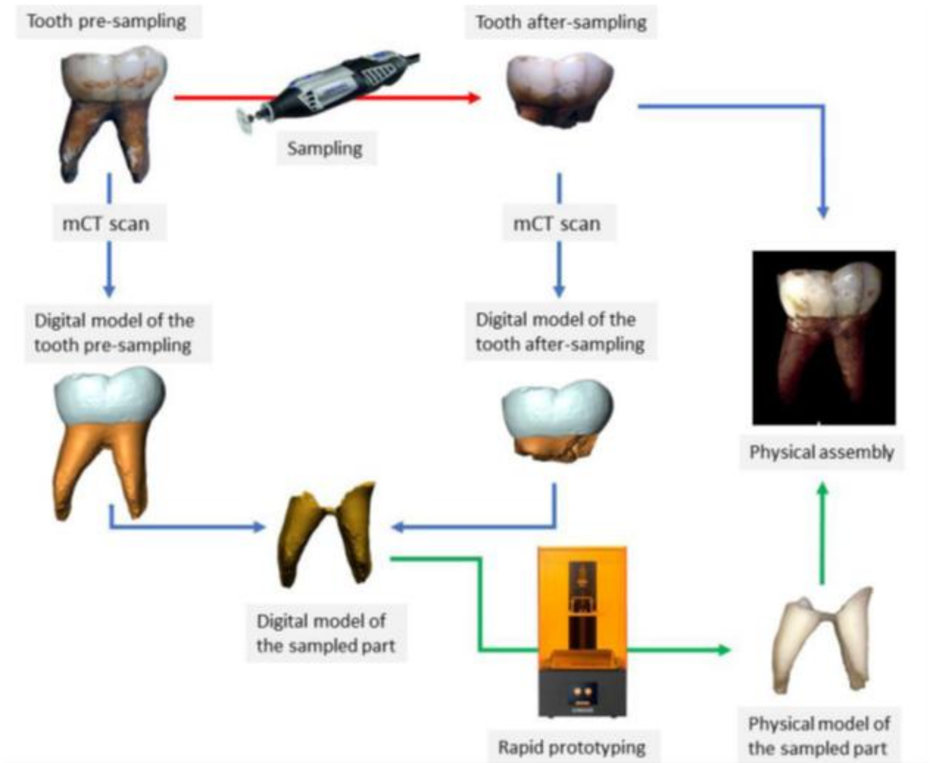

Fig. 4 Schematic of the different phases of the integrative restoration protocol

A) The archaeo-osteological samples were analysed using microcomputed tomography scanners.
B) The archaeo-osteological samples were sampled with a diamond blade. The samples were cut inside a laminar flow hood, designed for ancient DNA sampling, allowing very low levels of background contamination.
C) An additional computed tomographic scan was performed following the sampling.
D) MicroCT image data (pre- and post-sampling) were segmented automatically using Avizo Lite 9.2.0 software (Thermo Fisher Scientific) to render the pre- and post-sampling 3D digital models [GDTCMM18], [NNG15], which were then imported in Geomagic Design X (3D Systems) for cleaning processes and for the correction of incidental defects (e.g., filling of small holes) to create fully closed surfaces.

E) Different spline curves were digitized on the margins of the artificial cuts of the post-sampling digital models to isolate the cutting surfaces and create the negative versions of them. The pre- and post-sampling digital models were overlaid using the superimposition algorithm on Geomagic Design X software, and the previously created spline curves were projected onto the digital model of the whole artifact (pre-sampling) to isolate the sampled portion. Then, the negative of the cutting surface and the model of the sampled portion were merged in a single mesh and any discontinuity was removed [CVSBSSL21], [HMVBR19].

F) Exact replicas of the sampled portions were reproduced with rapid prototyping technology (LCD Stereolithography (SLA)) using an Orange 10 LCD 3D printer (Longer). The prototype was produced using Longer UV resin with a layer thickness of 0.05 mm, UV Matrix 405 nm LED lighting sources and slicing Longerware software (Longer).

G) Finally, the printed replicas were painted and applied onto the preserved original portions by using compatible and reversible glues (specifically UHU extra gel Polyvinylester).

To determine the accuracy of the replicas, the standard deviation between the surfaces of the original specimens and the ones of the prototyped products was calculated. To do this, the printed portions were also acquired through computerized micro-tomography, and their digital 3D surfaces (generated by following the segmentation methodologies described previously) were compared with the ones generated from the microCTs of the specimens prior to sampling by applying the standard deviation tool in Geomagic Design X between the meshes [B08].

Case study 1: Physical restoration after sampling of the human phalanx from

Obłazowa Cave, Early Upper Paleolithic site at, Poland.

Sampling a portion of the phalanx for ancient DNA (aDNA) and radiocarbon analyses required an integrative restoration intervention to restore the specimen's formal integrity, ensuring its conservation, suitability for museum exhibition, and potential for future morphometric analyses. Following the protocol outlined in Vazzana et al. (2022), the process involved several key stages.

Initially, microcomputed tomography (microCT) was performed on the phalanx to obtain precise measurements. After sampling, additional microCT scans were conducted on the epiphyses at the Department of Physics and Earth Sciences of the University of Ferrara using an isotropic voxel size of 30 µm. The microCT scanner operates with a sealed microfocus source (Hamamatsu L9181) at a voltage of 80 kV and a current of 90 µA. Pre- and post-sampling microCT image data were segmented semi-automatically using Avizo Lite 9.2.0 (Thermo Fisher Scientific) to generate 3D digital models **[GDTCMM18], [NNG15]**, (Fig. 5-6).

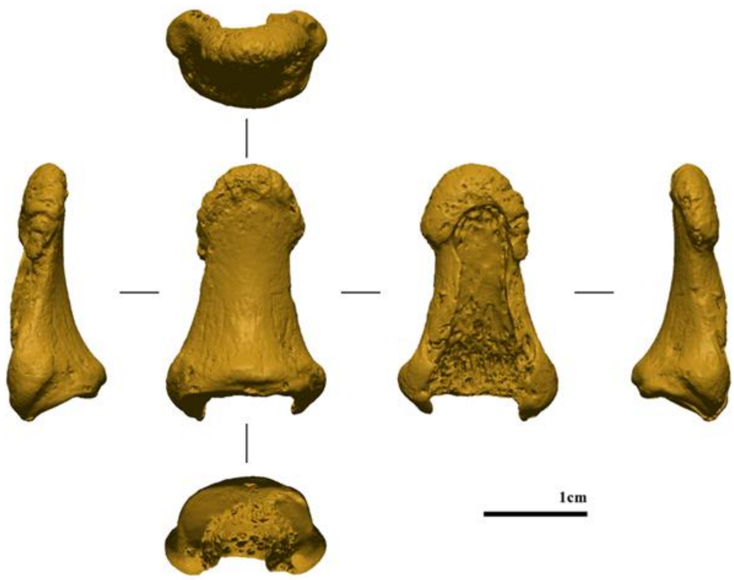

Fig. 5 Pre-sampling digital model (from left to right: ulnar, dorsal, palmar, and radial views).

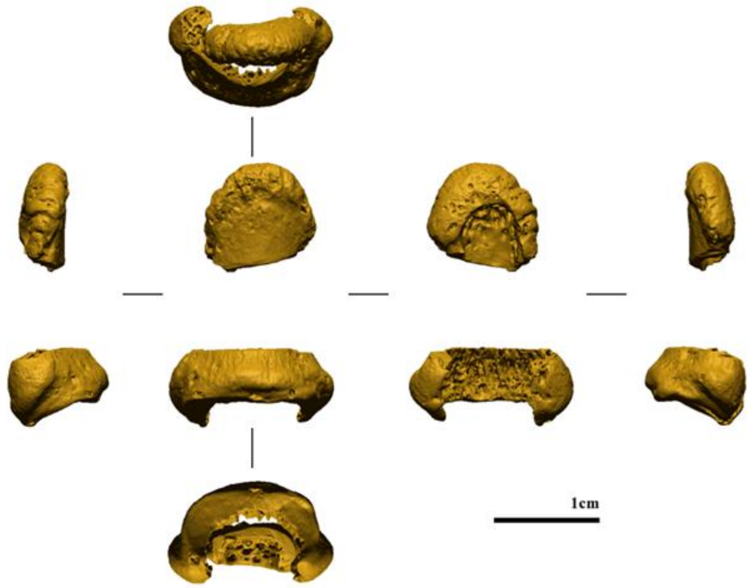

Fig. 6 Post-sampling digital model (from left to right: ulnar, dorsal, palmar, and radial views).

The models were postprocessed (e.g., closing small holes) on Geomagic Design X (3D Systems) to create fully closed surfaces.

Following Benazzi et al. [BGSH14], two spline curves were digitized along the margins of the artificial cut of the post-sampling digital model to isolate the cutting surface and create a negative version thereof. The pre- and post-sampling digital models were then superimposed using the superimposition algorithm in Geomagic Design X. The spline curves were then projected onto the pre-sampling digital model to isolate the sampled portion (Fig. 7) **[VST18]**. Finally, the negative of the cutting surface was then merged with the digital models of the sampled portion to produce a unified mesh, with any discontinuities rectified [CVSBSSL21], [HMVBR19], (Fig. 7).

Exact replicas of the sampled sections were produced using rapid prototyping technology, specifically LCD stereolithography (SLA) with an Anycubic Photon Mono X printer (Anycubic). The prototypes were created with Anycubic white Standard Resin, set to a layer thickness of 0.05 mm, utilizing UV Matrix 405 nm LED light sources, and were processed using Chitubox Basic V 2.1.0 slicing software (Shenzhen CBD Technology Co., Ltd. ("CBD-Tech")) (Fig. 7). Finally, the printed replicas of the sampled portions were attached to the preserved original sections with compatible and reversible adhesives (i.e., UHU extra gel Polyvinylester) (Fig. 8-9).

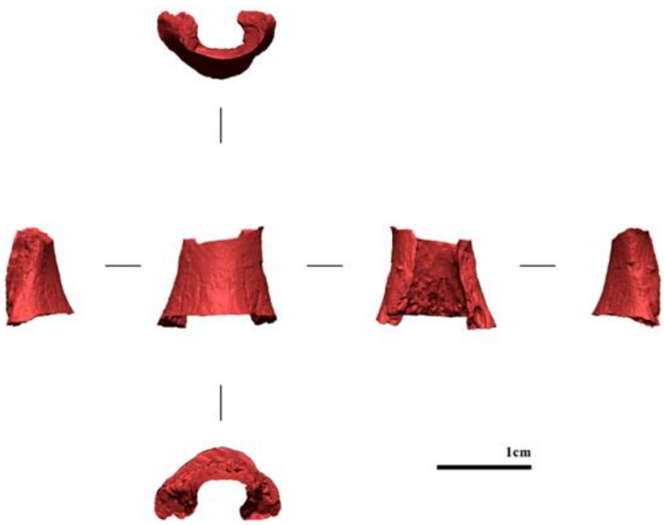

Fig. 7 Digital model of the sampled portion in all views (from left to right: ulnar, dorsal, palmar, and radial views).

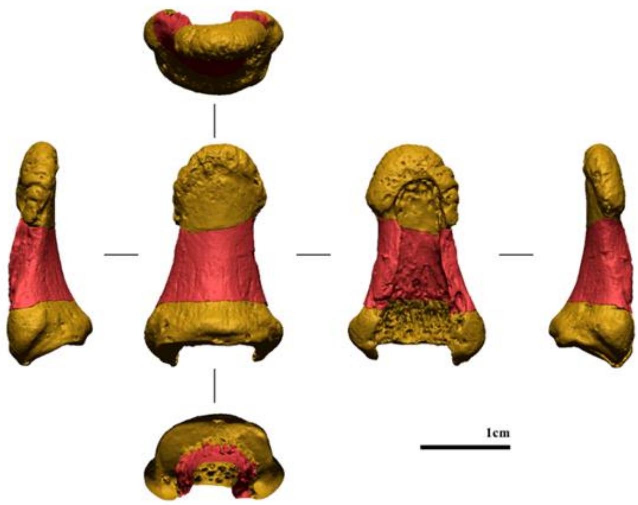

Fig. 8 Merged-digital model. The sampled portion is in red (from left to right: ulnar, dorsal, palmar, and radial views).

Fig. 9 Photographic record of the finding after physical restoration (from left to right: ulnar, dorsal, palmar, and radial views).

Case study 2: Physical restoration after sampling of the human tooth from Observatoire Cave, Paleolithic site in the Principality of Monaco (MC).

Sampling a root portion of the tooth for ancient DNA (aDNA) analyses required an integrative restoration intervention to restore the specimen's formal integrity, ensuring its conservation, suitability for museum exhibition, and potential for future morphometric analyses.

Initial measurements were obtained using microcomputed tomography (microCT) scanners. Following sampling (see above), an additional computed tomographic was carried out at the Department of Physics and Earth Science of the University of Ferrara and a virtual 3D reconstruction of the tooth was obtained using an isotropic voxel size of 30 μm. The microCT scanners is based on a sealed microfocus source (Hamamatsu L9181). The scan was carried out at a Voltage of 80 kV, a current of 90 μA. The pre- and post-sampling microCT image data were semi-automatically segmented using Avizo Lite 9.2.0 software (Thermo Fisher Scientific) to create 3D digital models [GDTCMM18], [NNG15]. These models were then imported into Geomagic Design X

(3D Systems) for cleaning and incidental defect correction (e.g., filling of small holes) to generate fully closed surfaces (Figures 10.1, 10.2; [HVSRBCBOB20], [VST18]. A spline curve was digitized along the margins of the artificial cut in the post-sampling digital model to isolate the cut surface and create its negative [BPFTGH14]. The pre- and post-sampling digital models were aligned using a superimposition algorithm in Geomagic Design X, and the spline curve was projected onto the complete tooth digital model (pre-sampling) to isolate the sampled section. Subsequently, the negative of the cut surface was merged with the model of the sampled section into a single mesh, removing any discontinuities [CVSBSSL21], [HMVBR19], [LNS22]. Exact replicas of the sampled sections were reproduced using rapid prototyping technology, specifically LCD stereolithography (SLA) with an Anycubic Photon Mono X printer (Anycubic). The prototypes were created using Anycubic white Standard Resin with a layer thickness of 0.05 mm, UV Matrix 405 nm LED light sources, and Chitubox Basic V 2.1.0 slicing software (Shenzhen CBD Technology Co., Ltd. ("CBD-Tech")). Finally, the printed replicas of the sampled portions were affixed to the preserved original sections with compatible and reversible adhesives (specifically UHU extra gel Polyvinylester; Figure 10.3).

Following the proposed protocol enabled the production of a physical replica with high fidelity to the original, achieving a precise correspondence between the contact surfaces of the original and reconstructed portions. Notably, this integrative restoration was achieved without the need for any manipulation or adaptation of either component (Figure 10).

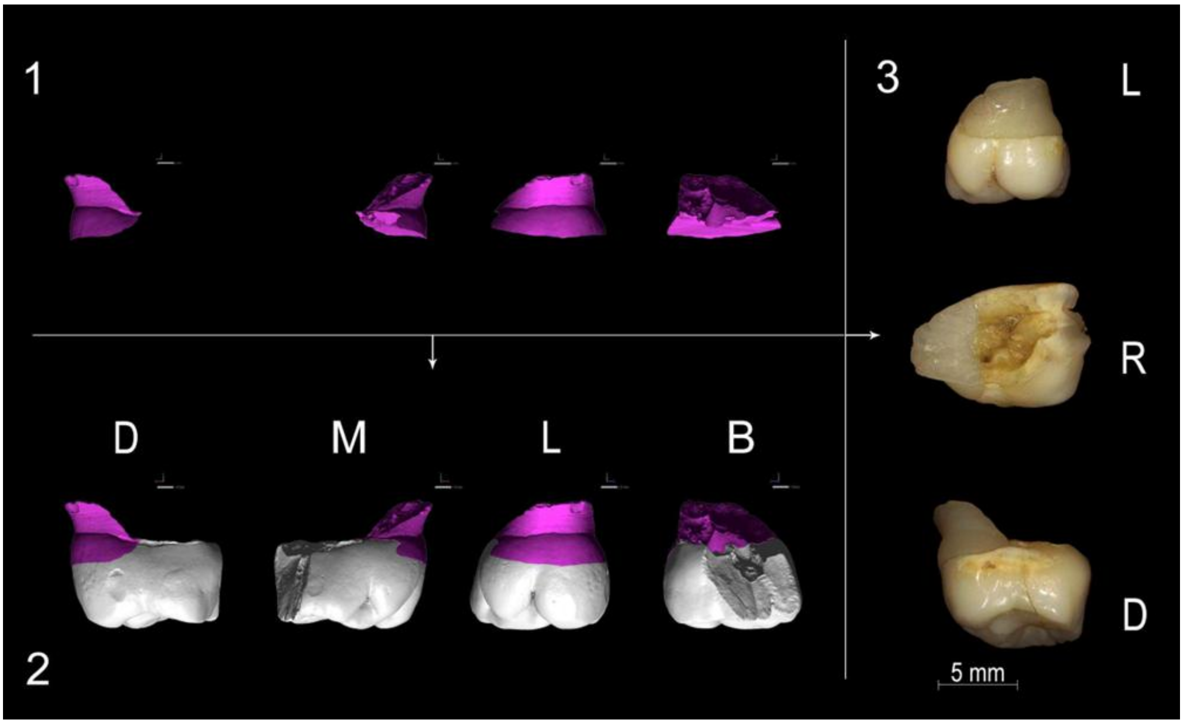

Fig.10 3D reconstruction, printing and restoration of the deciduous molar tooth of Observatoire Cave after root sampling for genetic analysis attempts. (1) 3D view of the sampled portion (approximately 0.3 g); (2) virtual reconstruction of the sampled tooth; (3) resin printing of the sampled portion and its replacement. D: distal, M: mesial, L: lingual and B: buccal view.

2.2.3 Conclusions

The outline of protocols designed for the accurate restoration of the morphological integrity of dental specimens and, in general, of osteological finds after sampling for chemical, physical and molecular analyses is becoming more and more of a necessity. The information that can be obtained through the application of this type of analyses, which are usually destructive or micro-destructive, has become essential to reconstruct with greater detail the life history of an individual.

The case studies here presented testify that the integration between RE, CAD and RP can help develop innovative restoration protocols characterized by a non-invasive and reversible approach. This method allows more thorough planning of any invasive sampling intervention, opening new perspectives in the bioarchaeological field.

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The mold-based techniques that are currently in use for physical restoration are well-proven, but much more rudimentary. They produce good results but cannot be used without physical manipulation of the original object, which serves as a model. This increases the risk of damaging or altering the find, whereas digital technology allows to overcome this problem.

The proposed method allows the design of the prototype of the missing/sampled portion through microCT analysis and 3D printing, and its application onto the preserved portion with minimal manipulation of the object.

The accuracy and reproducibility of the models provide a more durable, yet still tangible subject to study. In addition, in the case of museum exhibits, the viewer is enabled to appreciate the entire shape of the object, which – if deemed necessary – can also be scaled, increasing cognitive perception.

Currently, possible limitations of this methodology are related to RP materials, as there are no studies about their compatibility, strength, durability, and aging in different storage environments.

Our protocol, like the ones regarding virtual restoration with geometric morphometry techniques [CVSBSSL21], [HMVBR19], has the potential to revolutionize the field of restoration, not only of osteological finds, but also of movable and immovable objects of historical, artistic and archaeological interest like sculptures, bas-reliefs, architectural elements, and ceramics. In addition, its application can also impact the medical/orthopaedic field and improve the protocols that are currently in use in the creation of implants, which often need to be completely finished before implantation.

2.3 Advanced Sensing and Control Room for a long-term monitoring and safeguarding Cultural Heritage

2.3.1 Overview of GSSI's approach in the context of Spoke 5

As part of Spoke 5, the Gran Sasso Science Institute (GSSI) has established an interdisciplinary team comprising computer scientists, physicists, a technologist, and an art historian. The activities carried out within Spoke 5 are complementary to those of Spoke 7 - which also involves researchers from the Social Sciences area - and are focused on the prevention of natural, anthropogenic, and climate-related risks. Overall, GSSI's work is centred on the case study of *L'Aquila, historic city*.

For the research activities of Spoke 7, GSSI has signed a framework agreement that brings together various cultural stakeholders (including Superintendencies, Museums, Universities and Academies, the Regional Civil Protection Agency, among others), forming a network of expertise capable of monitoring the conservation status of sites and artworks, and intervening when necessary.

To support this network, and within the framework of Spoke 5, a software platform is currently under development for the acquisition and visualization of monitoring data from selected sites. These data will feed into a Control Room, hosted and managed by GSSI, equipped with a wall of seamlessly connected monitors for real-time visualization of environmental, structural, and infrastructural indicators. The Control Room will serve as a central node for integrated site supervision, offering tools for comparative analysis, alert management, and decision-making support.

In parallel, software is also being developed for a user interface (UI) that will allow stakeholders to easily access, analyse, and act upon the data-both in relation to urban heritage and, potentially, at the regional scale, once the network of sensors installed across sites in L'Aquila becomes a standard resource available to Superintendencies.

Simultaneously, sensor deployment has begun at sites identified as particularly in need of monitoring, or where restoration work on structures and decorative elements is in an advanced phase-given the ongoing post-earthquake reconstruction process. The aim is to embed monitoring within the virtuous cycle of post-restoration, enabling the prevention (or slowing) of renewed deterioration and allowing for the assessment of recently completed interventions.

2.3.2 Control Room: the software under development

A software platform for the network's Control Room is currently under development, along with the design of data acquisition protocols for the information collected by sensors installed throughout the historic centre of L'Aquila and its surrounding areas. These sensors, deployed both outdoor and indoor, are capable of monitoring various environmental parameters to identify, assess, and ultimately prevent degradation risk, at both the urban scale and that of individual buildings. This monitoring system is intended to support the implementation of risk mitigation strategies, whether within structures or on outdoor heritage assets.

Fig. 11 A preview of the future Control Room configuration.

The sensor network will continuously record key environmental variables such as temperature, humidity, wind, solar radiation, and atmospheric particulate matter. In parallel, Bluetooth sensors will monitor human presence and movement, providing useful data for analysing tourist flows, site accessibility and usability, and broader socioeconomic trends.

An automated Alert System is also planned, targeting heritage protection authorities. The system will trigger alerts whenever recorded parameters exceed optimal conservation thresholds, thus enabling prompt responses and contributing directly to cultural heritage monitoring through Internet of Things (IoT) solutions.

In addition, the Control Room will feature a visual interface of the historic city of L'Aquila, accessible remotely via secure credentials by regional Superintendency officials. This interface will provide detailed views of the monitored sites: by selecting a specific site, users will be able to access real-time data as well as temporal trends, visualized on an hourly or daily scale.

2.3.3 Sensors adopted and the first monitored site

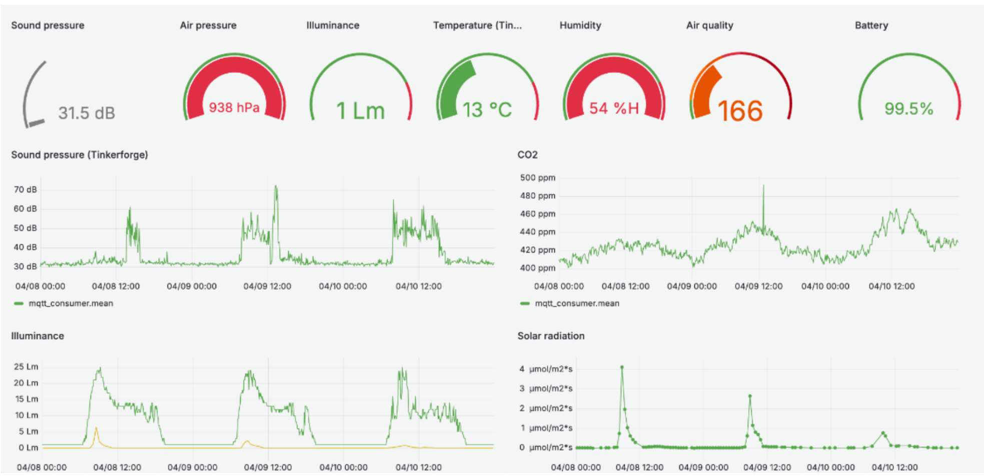

Fig. 12 The dashboard of microclimatic and ambiental data coming from the first site monitored.

It is instructive to present the assessments carried out during the planning phase of the monitoring system for the first identified case study: the Church of Santa Maria della Misericordia in L'Aquila. This small, single-nave church, originally built in the 16th century, is currently undergoing partial restoration. This circumstance has made it possible to initiate preliminary monitoring activities during the restoration phase itself, allowing for the observation of potential microclimatic variations within the building in relation to human presence, as well as the working conditions of on-site personnel. The selection of this specific building was motivated by several factors: in addition to being an active construction site, thus offering greater flexibility in the deployment and placement of sensors, it houses a series of frescoed wall paintings of considerable historical and artistic value. These frescoes were uncovered only after the earthquake, having been concealed for nearly three centuries (since the 18th century) behind Baroque partitions. They are now exposed to environmental conditions that may accelerate their degradation.

The sensor installation project is then described, making explicit the reasons for it, designed ad hoc based on the specifics of the building.

Fig. 13 First sensor board, approximately 25 cm x 30 cm in size.

2.3.4 WebApp for conservation operators

A web app has been developed to integrate the aforementioned IoT solutions with data concerning the physical, cognitive, and emotional states of restorers during their on-site activities. These data sources leverage artificial intelligence techniques to support ongoing restoration practices, complemented by visual documentation (photographs taken by the operator during the restoration process). All information is organized within an interactive dashboard that allows experts to monitor environmental parameters in the workspace, review the history of previous interventions, and discuss specific conservation issues encountered in other national and international case studies—automatically identified by the web app through open-access literature.

The web app provides restorers with a real-time tool for monitoring their work and receiving contextual support during interventions. In addition, automatic alert messages are triggered when the working environment becomes particularly unsuitable (e.g., excessively high humidity levels or poor air quality falling below acceptable thresholds).

The experimentation, initiated with the first case study involving the restoration of the Church of Santa Maria della Misericordia in L'Aquila, has demonstrated how digital technologies can effectively support restoration processes, while also ensuring the creation of a detailed and open-access historical record of the intervention.

2.3.5 A support for Cultural Heritage stakeholders

In the future, it will be crucial to compare sensor data with degradation models of the materials present at the sites of interest. This will assist stakeholders in making accurate diagnoses of the condition of cultural assets. The long-term objective is also to integrate data from multiple sources and locations, both indoor and outdoor (e.g., correlating them with climate data provided by Civil Protection services), to enhance the accuracy, reliability, and spatial coverage of the monitoring system. This integration will support the development of advanced preventive conservation strategies for cultural heritage.

This approach, combined with the development of the web application designed to support restoration processes and practitioners, provides a technical-scientific toolset for cultural heritage stakeholders, ranging from institutional bodies to individual professionals.

2.4 Visualizing Cultural Heritage diagnostic: integrating 3D models with other diagnostic data online

The CH domain requires diagnostic data, resulting from different analyses, to be managed using different approaches, archived in different storage systems, studied with different tools. Recent research efforts have been focused on improving the interoperability of CH diagnostic results, through the implementation of digital tools and platforms able to define a shared environment for data management and analysis.

Starting from these premises, in the framework of WP5 CNR-ISTI, in collaboration with UNICT partners, decided to explore the research space related to the design and the development of effective graphical user interfaces and visualization methods for assisting the collaborative study and interpretation of diagnostic data. Combining the know-how of experts active in diverse research fields (computer science, architecture, engineering, physic, sensors), we defined a set of digital tools enabling 3D-based interactive and integrate visualization of diagnostic resources widely exploited in CH. This work resulted in an integrated web platform, based on the 3DHOP framework [PCDCPS15] [PCS18], providing interactive visualization of different diagnostic data integrated with their reference 3D models.

The implemented resource provides data entry, interactive 3D model annotation and interrogation, plus a set of data-driven visualization modes specifically designed. The tool also provides data sharing and remote analysis and potentially enables interconnected features such as collaborative workflows and integration with other tools and systems, like repositories and external archives.

The system has been tested in a real scenario, resulting in a prototypal tool for the interactive visualization of digitized 3D models integrated with sensor data from autonomous measurement systems for microclimatic monitoring. It exploits the 3D and sensor datasets gathered within the context of the case study "Museo Civico Castello Ursino," which took place in Catania (IT) and was promoted through collaboration between CHANGES SPOKE 5 WP3 and WP5.

A second case study based on a real scenario is currently being implemented. Still promoted through collaboration between CHANGES SPOKE 5 WP3 and WP5, it aims at developing a resource for supporting the study of the mortars of Palazzo Biscari, one of the most important eighteenth-century private palazzi in Catania (IT). In this case study, the web platform will enable the integration of 3D data (digitizations of the perimeter walls of the historic building under investigation) with elemental and diffractometric analyses (performed on the mortars of the walls).
Through heterogeneous data integration, visualization, and annotation, the resources developed aims at promoting cooperative diagnostics interpretation in the field of heritage science, contributing to improving the efficiency and the impact of CH diagnostic analysis.

2.4.1 3D-based integration and visualization of microclimatic diagnostics

This research falls within the realms of digital surveing and three-dimensional modeling applied to the experimentation and validation of operational protocols and methodologies for data acquisition and processing, integrated with data obtained from various diagnostic investigations. In particular, in the context of the objectives previously mentioned in the section, this specific case study aims at defining an interactive platform to integrate 3D data and diagnostic datasets gathered through autonomous measurement systems for microclimate monitoring based on RH and temperature sensors.

The identified case study concerns the Art Gallery of the Civic Museum Castello Ursino in Catania. The Gallery is located on the first floor of the Castle and houses a vast collection of works resulting from purchases and donations. It consists of five rooms of different sizes and characteristics, among which the Parliament Room has been chosen. This is because, inside this room, three different sensor nodes — developed as part of WP3 — have been installed to monitor the microclimatic conditions in which the paintings are preserved. These sensors record temperature and relative humidity every 10 minutes in the immediate surroundings of the artworks. The data are first stored in the device's internal memory and later transmitted wirelessly via Bluetooth for subsequent collection and analysis. Before installation, the reliability of the sensor nodes was validated in a microclimatic chamber designed to maintain stable and well-defined environmental conditions over time. Additionally, an advanced version of the sensor node — featuring energy harvesting capabilities also through piezoelectric materials — was deployed to assess vibrations present in the same areas of the museum.

The activity carried out within WP5 involved an initial phase of digital surveying through the experimental use of a recent laser scanning technology: the Leica Geosystem's BLK2GO mobile laser scanner. The BLK2GO (scan rate: 420,000 pts/sec, ranges: up to 25 m, size: H 279mm, D 80mm, weight: 775 g) is a handheld device that uses a real-time LIDAR scanning and GrandSLAM technology. It represents a combination of LiDAR SLAM, Visual SLAM, and an IMU (Inertial Measurement Unit) technologies. The computation of instrument position and movement are based on LIDAR analyses of the surfaces, three cameras to identify similarities between sequential images and IMU movement sensing. Through this equipment, four rooms of the Art Gallery and the internal courtyard of the Castle were surveyed, resulting in a point cloud composed of approximately 32 million points (Fig. 14).

An additional digital survey campaign was carried out using a different type of laser scanner, the Leica BLK360 Imaging Laser Scanner (scan rate: 360.000 pts/sec, accuracy: 6mm at 10m / 8mm at 20m, ranges: up to 60 m, size: H 165mm, D 100mm, weight: 1 kg), equipment available in the Laboratory of Architectural Photogrammetry and Surveying "Luigi Andreozzi". Unlike the BLK2GO mobile LS, this is a terrestrial laser scanner that operates when mounted on tripods. Using the BLK360° LS, only the Parliament Room of the Pinacoteca in the Civic Museum Castello Ursino was surveyed, aiming to obtain a more geometrically accurate 3D model of the room. Given the characteristics of this laser scanner, 9 station points were required for the acquisition, one of which was conducted on the landing of the external staircase connecting the first floor to the internal courtyard. From this survey, a point cloud consisting of approximately 500 million points was obtained (Fig. 15).

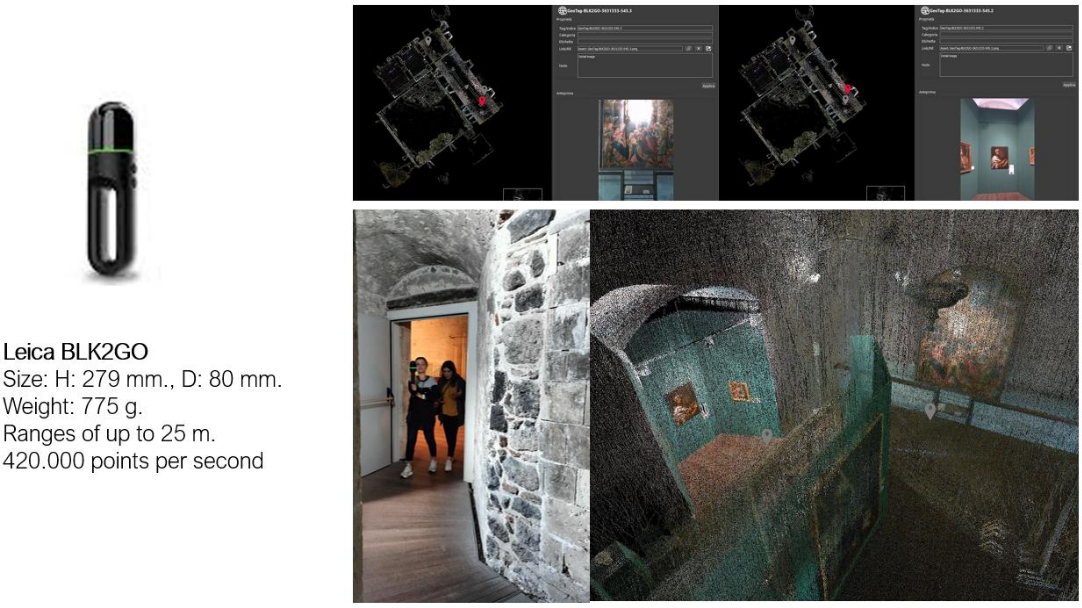

Fig. 14: The Pinacoteca of the Civic Museum Castello: results of the 3D survey executed with the BLK2GO system.

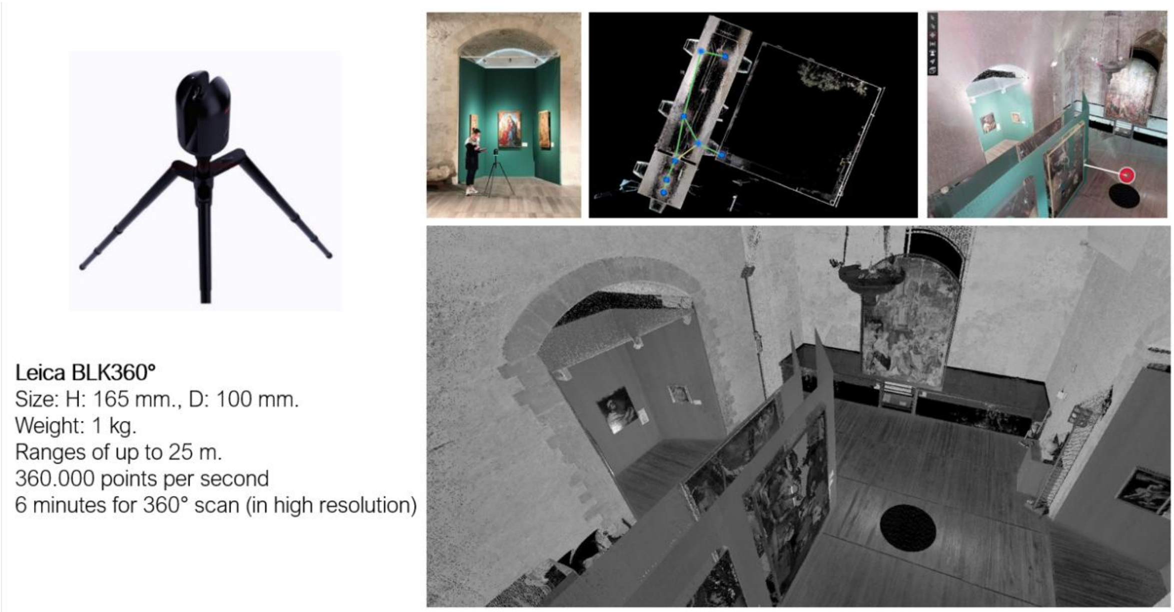

Fig. 15 Pinacoteca of the Civic Museum Castello: panoramic image survey performed with BLK360.

The final point cloud of the rooms of the Picture Gallery and the internal courtyard of the Castle was obtained by integrating the data of the two instruments used, the BLK360° LS and the BLK2GO LS. Both clouds were processed with the same reference system and then post-processed to eliminate noise such as visitors passing by.

The next step was to prepare the 3D models for the 3DHOP-based platform in charge of the application workflow for the assignment of the values obtained from the sensors (Temperature and Relative Humidity) to the three-dimensional geometries. From the point cloud (format .ptx) obtained from the integration of data from the two different laser scanners used (BLK360° and BLK2GO from Leica Geosystem), the polygonal model of the environments was derived, to be inserted into the platform.

The polygonal model loaded and visualised presents the texture obtained from the colorimetric data acquired by the cameras of the two laser scanners. To contextualise the environment under study and improve its visualisation, a low-resolution polygonal model of the exterior was also included (Fig. 16).

Fig. 16 Point cloud perspective view obtained from a photogrammetric survey of the exterior of the Museo Civico Castello Ursino in Catania.

The 3D models were finally converted into the Nexus multi-resolution format specifically designed for the web environment, so that the 3D geometries and the textures are displayed adaptively according to the distance and zoom of the user's view (Fig. 17).

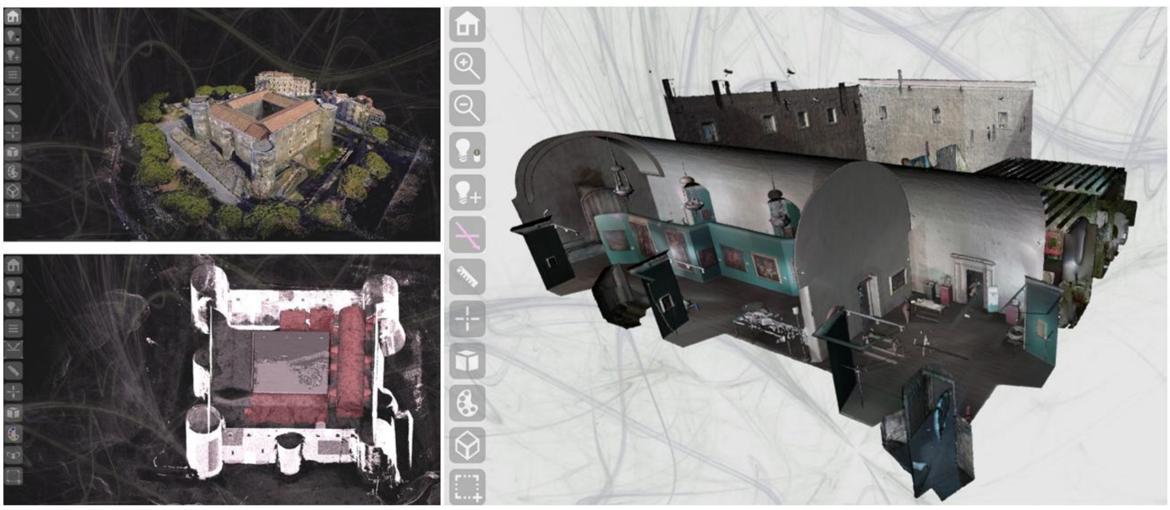

Fig. 17 3D model visualisation on the 3DHOP platform.

The developed platform enables access to these multiresolution 3D models through the web, and starting from the 3D scene, provides two main features: sensors setup and data navigation.

Concerning the sensor setup, the platform allows its users to dynamically add/remove sensors to the 3D scene and associate each sensor with the dataset of the values recorded (temperature and humidity, in our case), optionally enabling sensors customization (ID name, appearance, visibility, etc.).

Regarding data navigation, thanks to the developed platform the complete dataset linked to each sensor can be accessed via a dedicated panel (in tabular or graph form), while the most recent data recorded for each active sensor can also be interactively accessed by navigating the 3D model (mouse over the sensor spheres to get a pop-up message with the data). Moreover, the web platform also provides a complete set of features for the 3D viewer (rendering setup customization, visual bookmarks to predefined views, measurement tool, etc.).

In the current version, the main interface of the web platform is based on a single-page layout, composed of two sections: the 3D scene viewer, located on the left, and a multipurpose vertical panel, located on the right (Fig. 18-19). This simple front-end manages both data integration/annotation and data retrieval/visualization.

The 3D viewer encompasses a simple 3D scene aimed at the interactive visualization of the multiresolution digitization in which the diagnostic datasets are collected. The viewer also exhibits a multi-utility toolbar (top-left) and a navigation cube (top-right). Through the toolbar it is possible to access some tools specifically focused on 3D data investigation, including a measurement tool (for getting linear distances) and a sectioning tool (to enable axis-aligned "visibility cuts" of the 3D model in the scene), while the navigation cube, in addition to provide a visual reference on the orientation of the 3D scene, also enables direct access to six visual bookmarks linked to the six axis-aligned canonical views (top, bottom, left, right, front, back).

The vertical panel on the right is subdivided into 2 main sections: the upper one, providing features for the customization of the 3D scene rendering (including lighting control, projection views selection, switching between textures and solid colors, etc.), and the lower one, providing features for microclimatic diagnostic data management. The subsection aimed at diagnostic data management serves two different modes: 3D model annotation for the diagnostic data integration; and diagnostic data retrieval for the visualization of the datasets linked to each sensor station.

In data entry mode (Fig. 18) the platform allows to navigate the 3D scene and interactively positioning a sensor station simply picking a point of the 3D model. The added sensor station is represented by a sphere geometry characterized by set of customizable properties (name, color, dimension, visibility, etc.) reported in a specific tab in the right panel. Once a *sensor sphere* is added to the scene it can be linked to the dataset of value recorded (for example loading a CSV file), or it can be removed from the scene via a specific button.

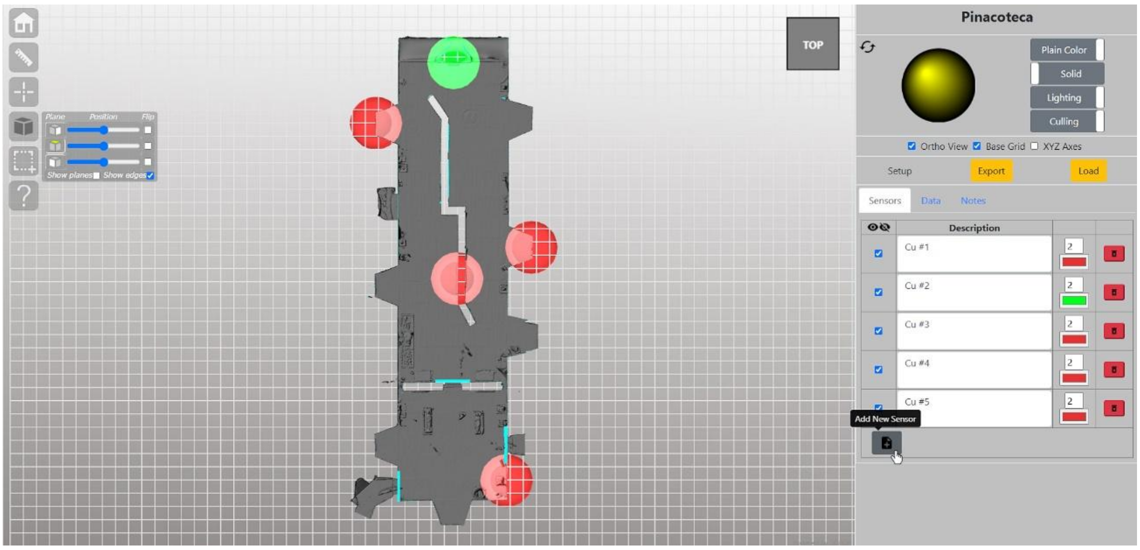

Fig. 18 3D model annotation in the web platform: in data entry mode it is possible to interactively add to the 3D model the sampling point related to each sensor station (red and green sphere in the figure); in this mode the panel on the right allows to link the created sensor stations with the recorded datasets and enables *sensor spheres* customization (name, color, dimension, visibility, etc.).

The diagnostic data associated with each sensor station can be retrieved in different ways (Fig. 19): navigating a specific tab of the right panel (in which all the data are reported both in tabular and graphical form), clicking one of the *sensor spheres* in the 3D scene (to get in the right panel only the dataset related to the specific sensor station), or simply positioning the mouse cursor over one of the *sensor spheres* (to get a popup message reporting the most recent data recorder by that specific sensor station).

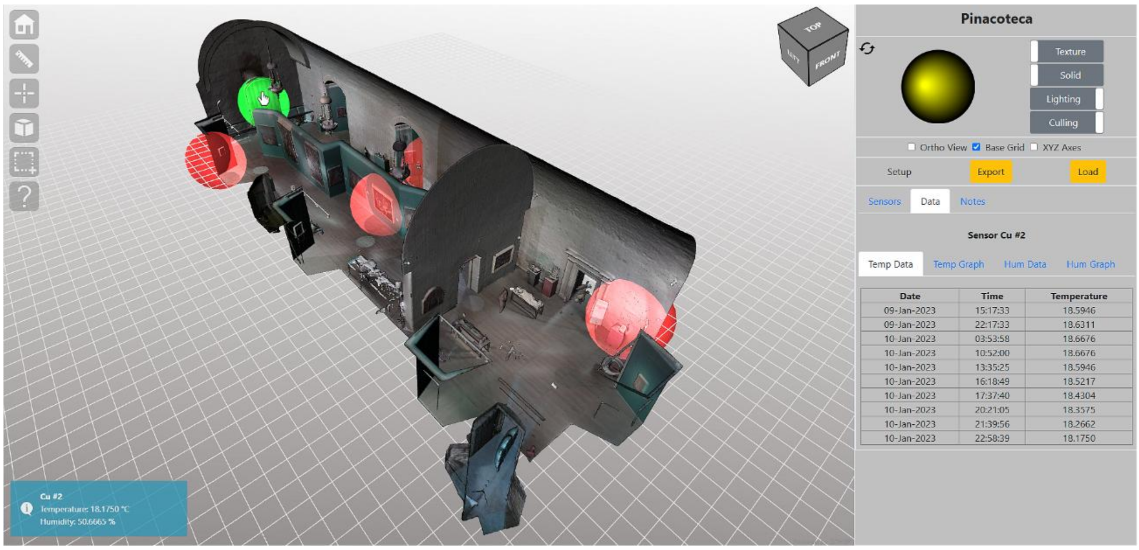

Fig. 19 Diagnostic data interrogation and visualization in the web platform: moving the mouse over an active sensor, the system shows the last recorded data (popup message on the bottom-left), while clicking on it, the informative panel on the right recalls the complete list of data associated with the sensor (in tabular form, in the selected tab).

A further tab is also provided by the system allows taking textual annotations in a free text box.

The whole sensor stations setup (*sensor spheres* positions, customizations, text notes, etc.) can be downloaded as a JSON file for backup or sharing reasons. In fact, the platform can be repopulated with the all the added info with a single click, just loading the JSON structure.

2.4.2 3D-based integration and visualization of materials science diagnostics

To further validate the set of tools developed for remotely managing and interactively visualizing in the same reference space different data resulting from diagnostics applied to CH, a second case study was implemented. Chosen to collaborate in the activities carried out under WP2, it interconnects the results of diagnostic investigations carried out on mortars typical of construction in the historical center of Catania. The chosen building is part of Palazzo Biscari, one of the most important eighteenth-century private palazzi in Catania, located in the Civita district of the city center. The part under study is located on the corner of Via Museo Biscari and Via Porticello and is in an evident state of decay. The original masonry is in some parts exposed, due to the absence of plaster, making it easier to remove the mortar. The methodology of diagnostic investigation and three-dimensional documentation proposed and tested in this phase is based on an interdisciplinary approach of specific skills and constant dialogue between diagnostics applied to the study and characterization of the mortars and the use of digital survey techniques useful for obtaining 3D models. More difficult, however, were the photogrammetric survey activities, as it is located in a very busy street, with cars parked close to the façades. The photogrammetric survey allowed an accurate mapping of the degradation, being useful to visualize accurately the data obtained from the diagnostic investigations. For the case study, a dataset of about 280 photographs was made, obtaining a point cloud of about 294,000,000 points (Fig. 20-21).

Fig. 20 Photogrammetric survey of the minor building in Catania's historic centre.

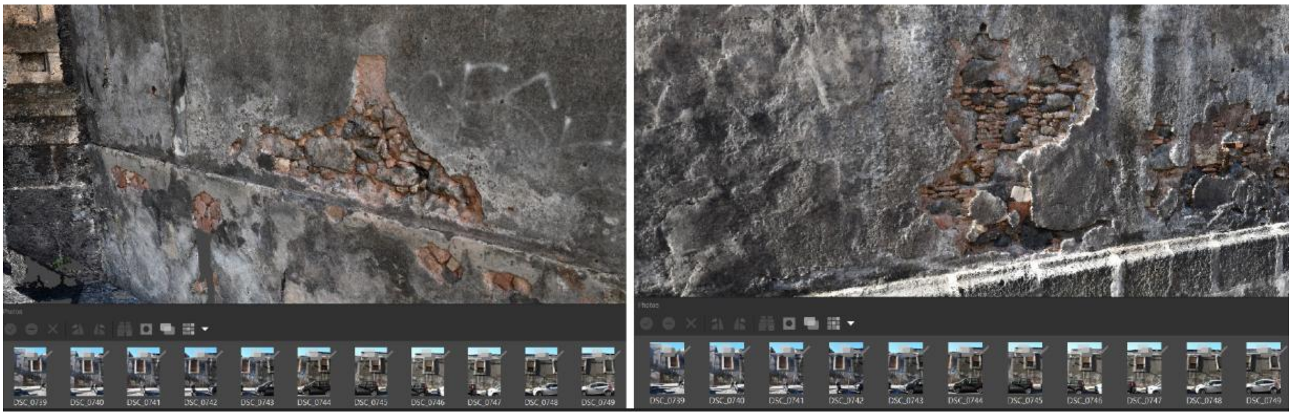

Fig. 21 Photogrammetric survey of the minor building in Catania's historic center – detail.

A digital survey was also conducted using laser scanning technology. The north elevation of this architecture was investigated. This elevation is approximately 46 metres long and presents some problems to carry out a correct metric acquisition, such as the cars parked in front of the elevation. This required a laser scanning survey to supplement the previous photogrammetric survey. Seventeen scans were carried out and a point cloud of approximately 304 million points was obtained (Fig. 22-23-24-25). Leica Geosystem's BLKK360 was used, which facilitated digital in-situ surveying activities due to its small size and good characteristics.

The 3D models from the digitization campaign are currently being processed to be converted in the web-friendly multiresolution format, to become ready to be ingested by the web platform (as in the previous case study).

The digital tools composing the web platform (still under definition), will be arranged this time and adapted to allow the integration of the mineralogical, petrographic, and geochemical analysis already performed at various points of the historical building. The planned features will include data fusion, visualization, annotation and interrogation capabilities, similar to those developed for the previous case study.

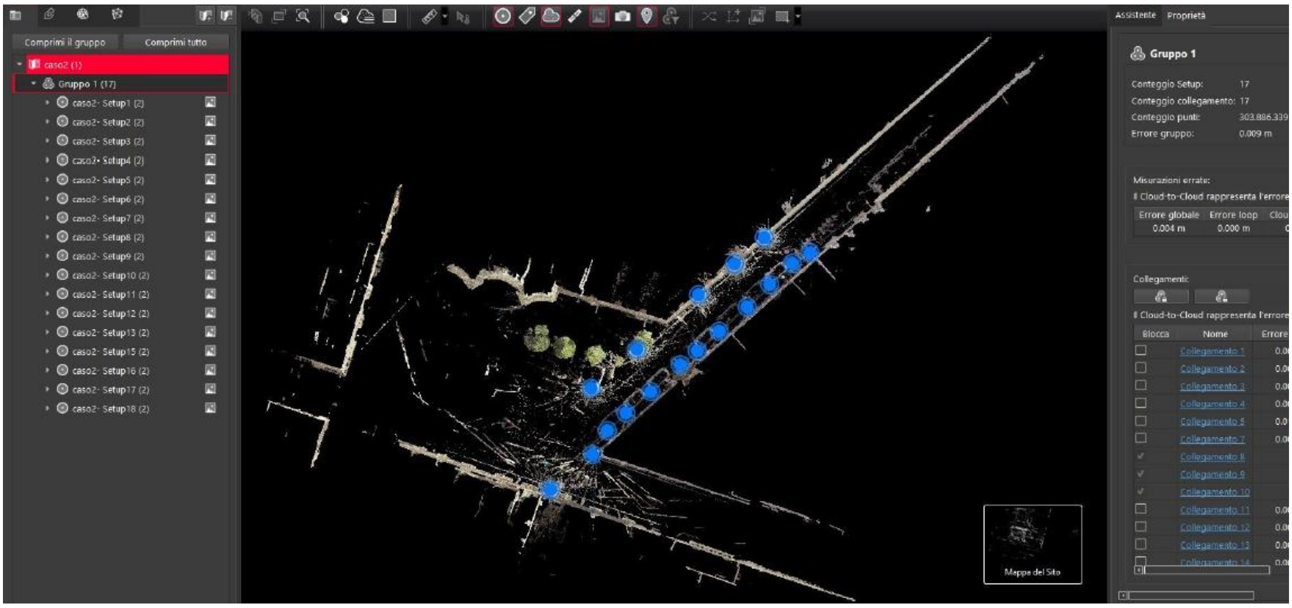

Fig. 22 Survey station points by BLK360° of the minor building in Catania's historic center.

Fig. 23: In situ survey activities.

Fig. 24 Perspective view of the point cloud of the minor building in Catania's historic centre.

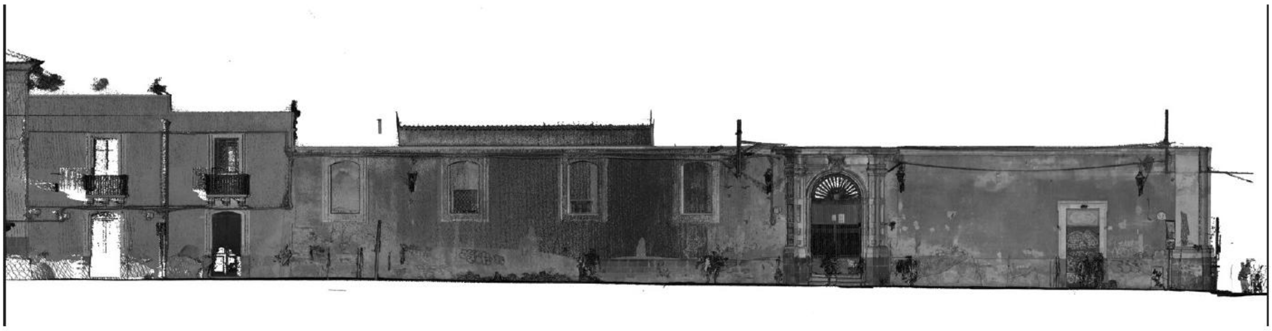

Fig. 25 Above, orthophoto from laser scanner survey; below, orthophoto from photogrammetric survey of the minor building in Catania's historic centre.

3. Conclusions

This report describes the advancements in the design and development of digital tools for CH management and analysis, in the framework of WP5 - Spoke 5 of the PNRR PE 5 "CHANGES" project. All the actions implemented, guided by previously identified user needs among CH stakeholders, aim to bridge existing gaps in data analysis software adoption and to enhance interactive visualization and data inspection capabilities. The achieved results underscore the transformative potential of integrating cutting-edge digital technologies, including AI, robotics, reverse engineering, rapid prototyping, advanced sensing, and online 3D visualization, to create a more efficient, precise, and collaborative framework for understanding and preserving cultural assets.

One pivotal area of development has been AI-powered digital tools for diagnostic analysis. A novel deep learning algorithm has been specifically engineered for the rapid and quantitative analysis of MA-XRF datasets from paintings. This algorithm, trained on synthetic spectra generated through Monte Carlo simulations of multi-layer pictorial stratigraphy, demonstrates superior accuracy in quantifying fluorescence line intensities and effectively eliminating artifacts that typically plague conventional methods, particularly in low signal-to-noise environments. Its successful application to Raphael paintings validates its capability for automated and precise MA-XRF map creation, offering a robust and generalizable solution for pictorial analysis. Concurrently, an interactive digital platform has been developed to control robotic spectrometers (XRF/IR) designed for non-invasive investigation of complex three-dimensional CH objects. This platform critically generates accurate 3D models of objects, which are then used for meticulous measurement planning and trajectory generation, ensuring optimal geometric conditions, consistent data quality, and collision avoidance on irregular and curved surfaces.

Furthermore, the project has established a high-accuracy digital methodology for the integrative restoration of missing parts, particularly for archaeological bone and dental remains. This innovative procedure leverages computed microtomography, reverse engineering, computer-aided design, and rapid prototyping to fabricate customized missing components. By performing microCT scans both before and after sampling, digitally reconstructing 3D surfaces, subtracting the preserved portions to model the missing elements, and then physically prototyping these parts, the methodology overcomes the inherent limitations of traditional manual approaches. Key benefits include a significant reduction in specimen handling and associated damage risks, the ability to explore multiple reconstruction hypotheses in the digital realm, and the production of highly faithful, reversible, and reproducible physical replicas for scientific, exhibition, or educational purposes. Case studies involving Paleolithic human phalanges and teeth have demonstrated the efficacy of this approach in restoring morphological integrity with high fidelity. Beyond osteoarchaeology, this methodology holds vast potential for the restoration of diverse art objects, such as sculptures, bas-reliefs, and architectural elements, and even for applications in the medical and orthopedicorthopaedic fields.

A crucial area of innovation has addressed the long-term monitoring and safeguarding of CH against natural, anthropogenic, and climate-related risks. A sophisticated software platform is under development for a central "Control Room," housed at the Gran Sasso Science Institute, designed for real-time visualization of environmental, structural, and infrastructural data from a distributed network of sensors. This integrated system incorporates an automated alert mechanism that activates when optimal conservation thresholds are exceeded, providing crucial support to heritage protection authorities. A complementary web application for restoration operators facilitates real-time monitoring of work environments and access to contextual information, fostering data-driven restoration practices and creating detailed historical records of interventions. The pilot implementation in L'Aquila's historic center, at the Church of Santa Maria della Misericordia, demonstrates the practical application of this system in preventing degradation and assessing post-restoration conditions. The long-term vision is to integrate data from multiple sources and locations to enhance the accuracy and coverage of the monitoring system, thereby supporting advanced preventive conservation strategies.

Finally, the project has tackled the challenge of visualizing and integrating heterogeneous diagnostic data with online 3D models. An integrated web platform, built upon the 3DHOP framework, has been designed to enable the interactive visualization of diagnostic data spatially mapped onto their reference 3D digital models. This resource significantly enhances the efficiency and impact of diagnostic analyses by facilitating annotation, data interrogation, and data-driven visualization, thereby promoting collaborative studies and remote access. Its effectiveness has been demonstrated through two distinct case studies in Catania: the integration of microclimatic data (temperature and humidity) within the Art Gallery of the Civic Museum Castello Ursino, and the integration of chemical and mineralogical analyses of mortars with 3D models of Palazzo Biscari facades (a case study currently under completion). These digital tools fundamentally contribute to fostering a cooperative interpretation of heritage science data.

Altogether, the activities detailed in this report collectively illustrate how the adoption of advanced digital technologies (encompassing AI, robotics, reverse engineering, rapid prototyping, IoT monitoring systems, and web-based 3D visualization platforms) is poised to revolutionize workflows across the CH sector. The presented experiences not only yield concrete tools for knowledge acquisition, restoration, and monitoring but also establish the foundational paradigm for a data-driven research approach that innovatively, collaboratively, and sustainably enhances the collection, integration, processing, visualization, and documentation of cultural heritage. These digitally-enabled solutions, tested in real-world scenarios, are indispensable for strengthening the knowledge consolidation process, leading to a more profound understanding and precise assessment of the conservation status of cultural assets.

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