Integrated survey and semantic deconstruction: The bell tower of the Melfi Cathedral (PZ) between HBIM informative digitalization and virtual fruition

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ABSTRACT
In recent years, the theme of technological evolution and digitalization has determined the construction of a different methodological research approach, which is based on the experimentation of innovative models to support the activities of survey, as well as structural and chemical analysis. This paper presents the results of an interdisciplinary work on the bell tower of the Melfi Cathedral (PZ), where integrated survey technologies and semantic analysis of architectural elements have been applied to develop advanced Heritage Building Information Modelling (HBIM) solutions. The HBIM model connects geometric and informational data through defined parameters, preventing data redundancy and fostering more conscious heritage management. Three-dimensional survey campaigns generated georeferenced point clouds, forming the basis for the digital twin of the structure. This data-driven approach also supports immersive storytelling. A virtual tour of the bell tower was created, structured around the HBIM model and its Level of Information (LOI). Elements with higher LOI are prioritized in the narrative for their historical and heritage value. This immersive experience enables visitors to explore the architectural spaces, while simultaneously accessing data about structural conditions, material analyses, and sampling results. The result is a comprehensive, informative, and engaging atlas that supports both public education and conservation planning.

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1. INTRODUCTION

The process of introducing new technologies into more established survey and analysis methodologies, both structural and chemical-physical, constitutes a fundamental research issue. In contemporary debate, this topic is linked to the enhancement and conservation of historic properties, which increasingly require conservation actions or restoration interventions.

The effects of the digital revolution are increasingly evident through the widespread development of expedients that have altered the usual techniques of acquiring, communicating, and perceiving reality [1]. Preserving cultural heritage is, nowadays, a goal that the Architecture, Engineering, and Construction (AEC) industry has set out to protect. This important goal has defined a stretching of the horizon to other disciplines, and a reflection on the case study in both bibliographic and operational terms, to codify tools for integrated surveying. It is a tool that allows the

consolidation of a database and the possibility of finding the information entered during the process that affected the architectural asset.

The research on the case study of the Norman bell tower of Melfi Cathedral (PZ) experiments a different methodological approach, capable of weaving a relational link between historical heritage, innovative integrated survey methodologies using various technologies, Heritage Building Information Modelling (HBIM), and immersive digital technologies, thus defining innovative prospects for development.

This different methodological approach does not mean that data and information are transferred uncritically, without rigorously measuring the actual impact in terms of interoperable and multidisciplinary workflow (Figure 1). It defines a revolution of traditional analytical tools of surveys to elaborate immersive, interpretive and informative storytelling. Digital storytelling [2], [3] determines the paradigm shift in which «everything revolves
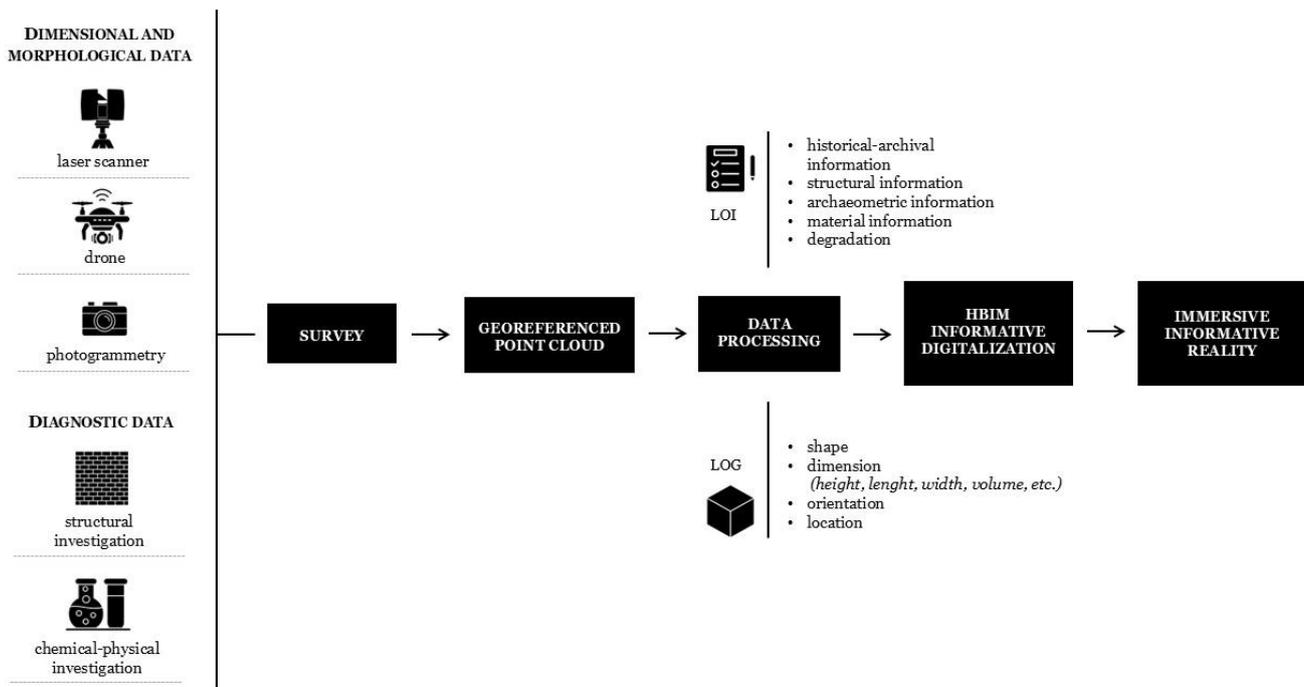
Figure 1. Schematic diagram of the integration between the different phases of the study [Istemi© s.r.l.].

around the idea of combining the art of storytelling with a medial and digital variety, in terms of the confluence of images, audio and video» [4].

The support of HBIM, derived from metric acquisitions and understood as a detailed representation of a building generated through intelligent components, is an effective solution for the digital representation of historical heritage. Experimentations with the integrated survey and semantic deconstruction of such components prove to be advanced HBIM modelling tools [5], aiming at the knowledge, preservation, and maintenance of the architectural artifact. Rooted in parametric design, the HBIM informative digitalization of the data of the survey on the bell tower aims to hold together the geometric part (Level of Geometry, LOG) and the information part (Level of Information, LOI). The generated model includes geometric information about the building components, as well as information about its entity, ensuring a simplified interdisciplinary approach in a shared environment that can be easily implemented and updated.

Following such instances of preservation and protection, this research proposes the creation of an immersive database through virtual tours for planned maintenance and innovative fruition, starting with the integration of advanced surveying techniques and the construction of an HBIM model.

2. INFORMATIVE DIGITALIZATION AND H-BIM MODELLING

The Norman bell tower of the Cathedral of Santa Maria Assunta in Melfi (PZ), the work of Noslo de Remerio commissioned by Ruggiero II in 1153, constitutes the only structure belonging to the original project, apart from the pinnacle, rebuilt after the 1851 earthquake, and the cathedral, heavily renovated in the 18th century.

The imposing quadrangular mole (9,25 meters on each side), set in the centre of the historic town (Figure 2), features a structure of well-connected limestone ashlars, according to a style widespread at the time between Sannio and Puglia. Originally free on all sides, the bell tower is built on several levels.

The first floor shows the epigraphs and lion protomes at the string-course cornice, on which the slightly tapered second level rests. The last two levels, characterized by the mullioned windows that lighten their mass, show a rich decorative apparatus with lava stone inlays depicting triangles, lozenges and inserts of *opus reticulatum*. On the main wall, on each side of the opening to the fourth floor, a pair of winged animals in *opus sectile* stands out [6].

Classical advanced acquisition methods [7], [8], such as laser scanning, drone, and photogrammetry, structured the first phase of data acquisition and survey carried out on the bell tower. At this stage, the study focused on reading and graphically restoring the geometries and constitutive elements of the architecture.

No-contact techniques based on both laser-based and image-based technology were used, exploiting laser scanning, drones, and photography in an integrated way to document not only the geometry but also the state of preservation.

The Terrestrial Laser Scanner (TLS) system, executed with Leica RTC360, was adopted for the high-resolution acquisition of the morphometric consistencies of the bell tower, while the Remotely Piloted Aircraft System (SAPR), executed with DJI -

Figure 2. Geographic frame of the historic centre of Melfi and location of the bell tower of the Cathedral [Istemi© s.r.l.].

MATRICE 210, was used to acquire images documenting the cultural asset in relation to the considerable height of the bell tower (52 meters). Through programmed flight operations, these images were acquired for digital photogrammetry [9], allowing the construction of photo plans of the bell tower's four elevations, through the graphic reprocessing work in Agisoft Metashape Professional software, defining a useful output for the mapping phases [10] of materials and degradation (Figure 3).

Figure 3. Architectural survey, photogrammetry and degradation analysis [Istemi© s.r.l.].
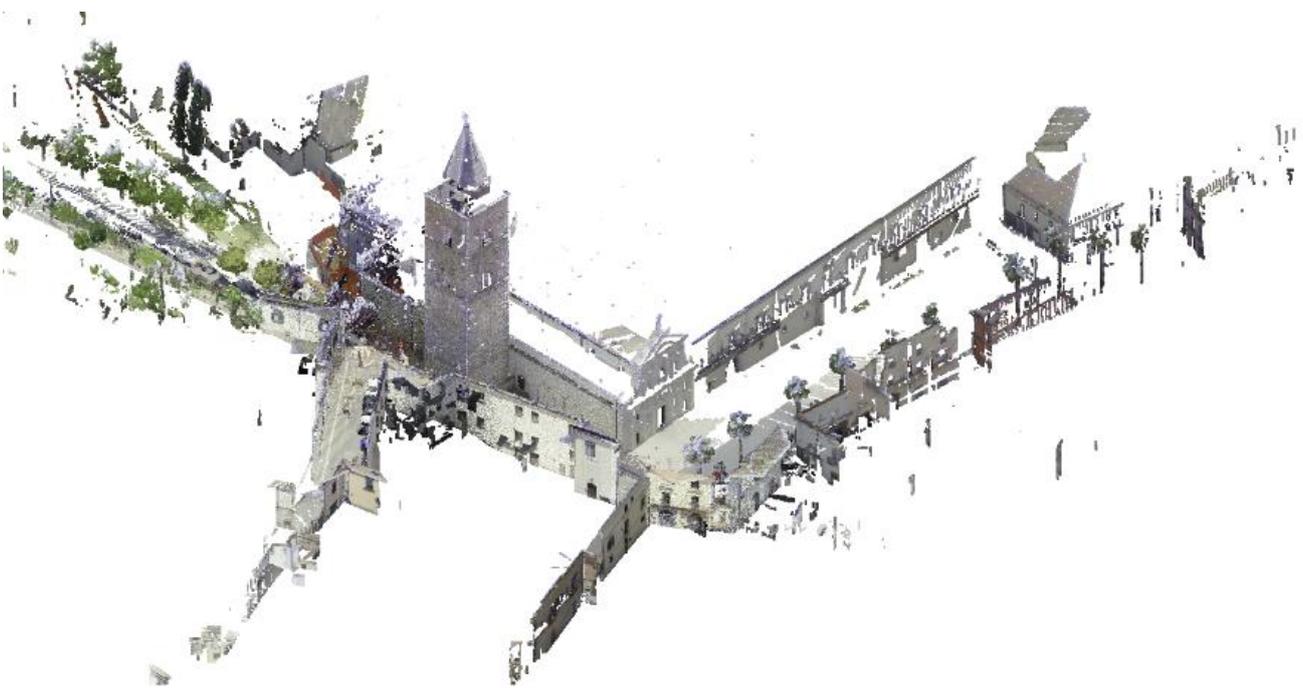
Figure 4. Graphic processing of the point cloud of the bell tower of the Melfi Cathedral [Istemi Srl©].

By integrating geometric and material data in the same workflow, the survey methodology [11], [12], employed for both exterior and interior spaces, returned a measurable, dense, and georeferenced point cloud (Figure 4), which formed the metric basis and spatial reference for subsequent processing of the HBIM model [13]. Data processing and processing operations were defined by taking into consideration the characteristics and qualitative capabilities of the instruments used for the purpose of mutual integration of the surveyed data. Therefore, the integrated survey operations have aimed at the creation of a reusable and implementable framework for transforming the point cloud set into a semantic model.

The second phase of the study corresponds to the process of the informative digitalization of the model, aiming at defining the digital twin [14]. This phase focuses the experimentation on a critical reconstruction of the geometric components and architectural forms of the bell tower.

These features were imported to Autodesk Revit [15], where all the constitutive elements of the bell tower (Figure 5), such as the pilasters and string courses, double-arched windows and the pinnacle, as well as the articulation of the interior spaces, were modelled according to a LOD E (object specific) Level of Detail [16]. This Level of Detail assumed an important role and most of the survey and design data were referenced to it. The set of
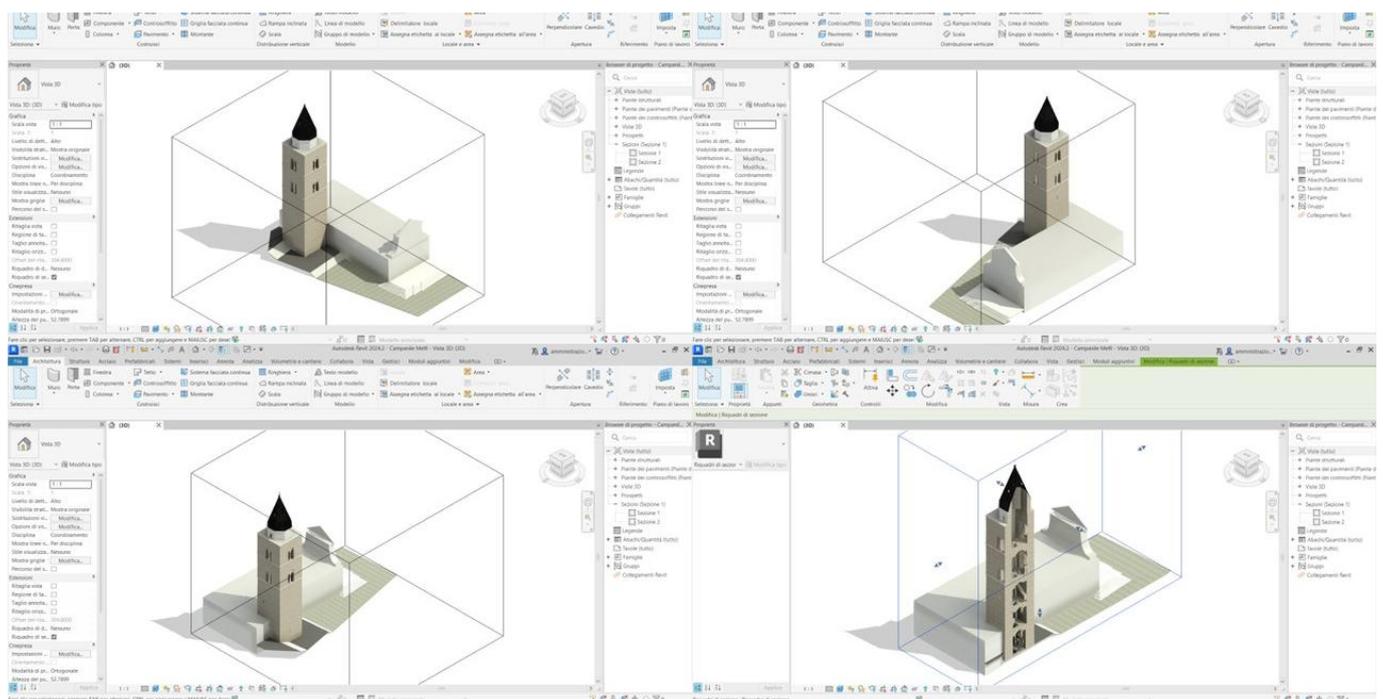

Figure 5. HBIM modelling process of the bell tower, with nearby open spaces and the footprint of the Melfi Cathedral, in Autodesk Revit [Istemi© s.r.l.].

historical-archival and analytical documents of the historic building is linked to the model elements and collected in a database in the form of integrated or linked data. The Level of Information (LOI), by avoiding a redundancy of data, has enabled a more careful overall reading, which may be the key to more reasoned interventions. The correct organization of data in databases, structured from a management perspective, could ensure a more efficient maintenance of the historical artifact [17].

At the end of the modelling process, it was decided to set up a database suitable for collecting the different information derived from the structural, material, and chemical-physical analyses. In this way, information regarding transformations over time, information on restorations carried out, documentation of inspections, further interventions, surveys, degradations, and investigations can be brought together in a single virtual data environment. The model is continuously implementable; thus, the database is constantly updated, searchable, and easily interrogable.

Due to the union of integrated survey operations and semantic deconstruction of the acquired data, HBIM informative digitalization experiments with a methodology capable of storing geometric and documentary data together.

Thus, it becomes possible to obtain an easily searchable model in which the whole compendium of information, historical and technical, often dispersed among different sources, converges in the same virtual environment. The digital twin of the bell tower, through the creation of specific parameters, made it possible to link the geometric part and the informative part, related to different areas and disciplines.

3. VIRTUAL FRUITION AND DIGITAL DATABASE

The development of the concept of digital infrastructures is spread in the field of cultural heritage through an increasingly frequent use of digital and virtual devices [18], [19], [20], which have outlined the possibility of "the creation of a technological ecosystem in which, starting from digital images, the management of heritage in terms of valorization and digital museographic operations represents an elusive concept, untranslatable, a real 'chimera', which, however, can be recognized as open, because it includes every possible initiative aimed at increasing the enjoyment of cultural heritage, and dynamic, as the expression of a process of transformation of the ways of enjoying the values of which the goods themselves are bearers" [21].

The research on the case study of the bell tower of the Melfi Cathedral considers new methodologies of virtual fruition, not only from the perspective of making the heritage an immersive experience through a combination of images, sounds, and colours. It also considers, in the informational logic, the built heritage as a container of multiple data. In this sense, the experiment has developed a model of the bell tower as a hypermodel to serve as a digital database that can be experienced through virtual tours.

The main goal of the digital database [22], from the HBIM perspective, is to create an innovative support for the conservation and management of the built heritage, making accessible data from structural, material, and chemical-physical investigations performed in situ and laboratory tests always performed ex situ. Bringing together in a single platform the information, related to different spheres of knowledge and coming from heterogeneous sources, allows to interact with unambiguous data, avoiding redundancy and dispersion. All the information used for modelling has been linked to the respective virtualized components, associating an image parameter with the different categories of objects.

This integrated approach allows for increased reliability in the investigation phase and, consequently, contributes to a more accurate knowledge of the architectural artifact, leading to more informed management and intervention protocols.

Contextually, the development of the virtual tour of the bell tower is the final phase of the project with a communicative and promotional aim, considering different types of users and needs. Virtual tours (Figure 6), integrated with AR, VR, and MR technologies [23], [24], [25], recode the relationship with visitors and expand to a diversified audience, as a result of a mass market
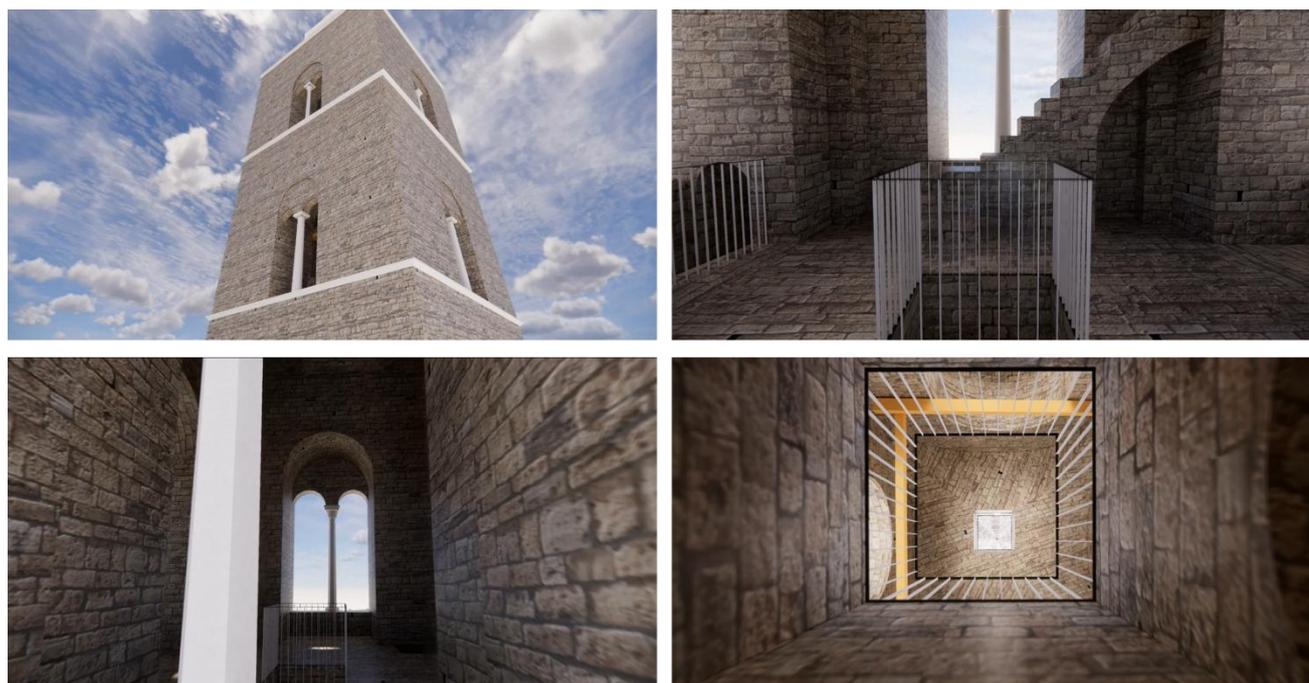

Figure 6. Virtual tour of both the internal and external spaces in HBIM environment [Istemi© s.r.l.].

that, consisting of mobile devices, smartphones, and tablets equipped with an increasing number of sensors, turns out to be able to facilitate user interaction significantly improving the enjoyment of cultural places [26].

In this digitally created virtual space, users can move freely and explore every part of the space that has been reproduced, while also overcoming any physical limitations. Through the proposed virtual tour, visitors can access both general and specific information in a simultaneous view, and they can enjoy virtual itineraries of the architectural spaces of the bell tower. This system provides a tool for in-depth knowledge and opens up interesting scenarios. Using such a cognitive platform, side by side with the real consistency of the architecture, it provides access to information and allows queries by users, who can access organized and structured data concerning history or even technical aspects.

By detaching themselves from the aesthetic logic of graphic restitution, visitors can learn about the state of conservation of the architectural artifact through the location and results of structural and chemical-physical analyses, as well as the performed related sampling, thus creating a narrative and informative path, together with an articulated atlas [27], [28], [29]. The hypertext graphic representation in the hypermodel of the bell tower has linked the technical specifications of the investigations and diagnostics with interactive enjoyment, allowing the immediate visualization of the cards related to the investigations, with numerical and thematic indications of the samplings, as well as with specifications of the scientific results obtained.

Performing chemical-physical laboratory tests, not only to learn about the materials and pathologies in place, but to understand what materials to use in the phase of filling gaps or replacing elements, highlighted the opportunity and need to localize the survey data in a punctual way. The dimensional data contributed to the understanding of the heterogeneous, yet similar forms made on the walls of the bell tower (Figure 7).

In this way, the digital twin of the bell tower of Melfi Cathedral creates a system that corroborates the meaning of knowledge and dissemination of cultural heritage, preparing digital models of the real object, which contain information and allow users to navigate the informative digital model, and, at the same time, visualize integrated data related to the parts of the architectural artifact.

4. CONCLUSIONS

The conclusions that can be drawn from the results of the research presented on the case study of the bell tower of the Cathedral of Melfi, reflect on operational methods, solutions, and difficulties concerning semantically structured models in the field of historical heritage.

The outlined experiment transforms and updates the traditional survey approach by integrating digital technologies, tools currently in use, and methodological rigor, consistent with references such as the Architectural Survey Map (1999) [30] or the London Charter (2009) [31].

The complex process of translating the forms of the bell tower's historical architecture into virtual environment information has the aim of preserving the extent of the building components, while ensuring the level of accuracy and reliability of the data. Basing the model on a reconstruction obtained from surveys using the combination of a laser scanner, a drone, and photogrammetry, the point cloud ensured a verification system

of the reconstructed model in the HBIM environment [32], [33]. These useful tools for measuring the reliability of the visualized data provided an important support for a correct transcription of the digital data, while considering the level of geometric abstraction of the converted data, as well as issues related to LOG (Level of Geometry) and LOI (Level of Information).

Therefore, by experimenting with the application of digital information tools that consider the interaction between the different disciplines involved in the case study, the research proposes a methodology aimed at the realization of a three-dimensional, interdisciplinary, implementable, and scalable information system, which is, nonetheless, propaedeutic to the setting of design and maintenance activities. The obtained semantic-aware [34] digital information model becomes the cultural and technical basis for representing the ontological reality of the built heritage regarding its geometric components, derived from the survey and post-processing of the point cloud, and in its technological and material characteristics.

Contextually, these tools become opportunities to strengthen the preservation and enhancement of cultural heritage by allowing suggestive insights into the reconstructed model or some of its parts. Thus, innovative scenarios emerge, in which general users can enjoy such immersive models, selecting components of them and viewing all the associated information through digital databases and specific cards. The result is the possibility of inclusive dissemination, which can support the learning process with innovative and interesting tools for use with devices such as tablets and smartphones.

In this paper, the authors aimed to investigate the effectiveness of integrated survey and HBIM modelling as valuable tools for the study, conservation, and maintenance of architectural heritage, evaluating the strengths and weaknesses of the parametric approach applied to existing heritage. This form of integrated surveying and semantic deconstruction in HBIM
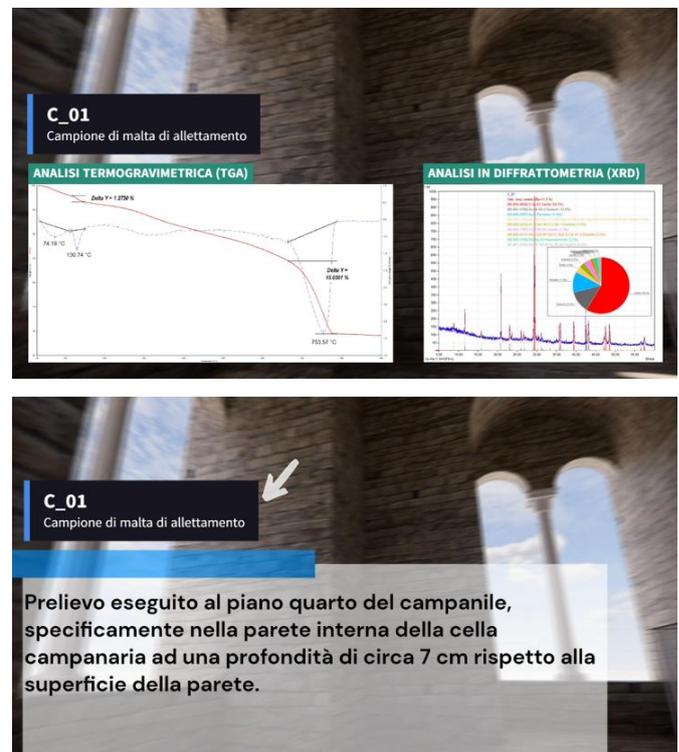

Figure 7. Hypertext cards with information on structural and chemical-physical analysis [Istemi© s.r.l.].

constitutes a starting point and a critical perspective, from which it will be possible to conduct other significant case studies and develop activities related to the preservation, enjoyment, and enhancement of cultural heritage, both in its tangible dimensions, i.e. the heritage itself, and in its intangible ones, i.e. management of data, models, as well as material, structural, and chemical-physical analyses.

AUTHORS' CONTRIBUTION

Conceptualization: Marianna Sergio and Eduardo Caliano; methodology: Marianna Sergio; software: Marianna Sergio and Nicolino Messuti; validation: Eduardo Caliano; investigation: Marianna Sergio, Nicolino Messuti, Cinzia D'Amico, Chiara Gallo, and Giada M.C. Gemelli; resources: Cinzia D'Amico, Chiara Gallo, and Giada M.C. Gemelli; data curation: Nicolino Messuti, Chiara Gallo, and Giada M.C. Gemelli; writing—original draft preparation: Marianna Sergio; writing—review and editing: Marianna Sergio; visualization: Marianna Sergio; supervision: Eduardo Caliano; project administration: Cinzia D'Amico and Ylenia Caso.

All authors have read and agreed to the published version of the manuscript.

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