The use of a Heritage Building Information Model as an effective tool for planning restoration and diagnostic activities: the example of the Troia Cathedral rose window

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ABSTRACT
The constructive reading of the historical architecture through the study of the published and unpublished sources preserved in the archives, can represent a unique and precious cognitive tool to acquire all fundamental information that constitutes the basis of an aware restoration intervention.
Frequently, in case of ancient buildings, reconstruct the complete history of the building is not possible, as the sources are difficult to find, not published or kept in different territorial institutes that are not always easily accessible.
The aim of this work is to set up an HBIM (Heritage Building Information Model) system to facilitate the planning of diagnostic and restoration activities by bringing all archive information into a unique digital reference platform, accompanied by three-dimensional models that can be consulted, examined and updated.
The creation of the HBIM digital tool for consulting the architectural artefact and related information was only the last phase of this work, which began with: (i) Acquisition of archive sources in order to reconstruct the history of the restoration and renovation work on the monument; (ii) Acquisition of information about the diagnostic analyses and monitoring previously carried out on the monument; (iii) acquisition of data useful for the creation of a digital twin.

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INTRODUCTION

The analysis of the published and unpublished sources preserved in the archives, together with all the due investigations on their physical consistency and the information that can be obtained from the diagnostic campaigns, can represent a unique and precious cognitive tool for acquiring the entire corpus of fundamental information about historical architectures, as a basis for a conscious restoration intervention.

In the case of ancient buildings, it is often not possible to reconstruct the complete history of the property, due to a lack of sources and because the existing archival Heritage is not known in depth because it has not been completely inventoried or is kept in various Cultural Institutions (public and private archives, libraries, and Superintendencies) that are not always quickly and easily accessible.

Systematising all this historical and technical information and making it directly available for consultation could therefore be a useful tool for scientific research and cultural dissemination.

Such a tool is indeed extremely useful for planning and decision-making in the Cultural Heritage sector.

Direct access to this body of information will facilitate and improve the quality of the conservation and enhancement work carried out by technicians.

The rethinking of this system, by channelling all the data into a single reference tool, can therefore allow a complete knowledge and anamnesis of the Heritage, avoiding incorrect planning choices due to the lack of an adequate cognitive substratum of the architecture.

All sources of information, in addition to historical and archival data, must be taken into account in a comprehensive approach aimed at improving the historical-constructive knowledge of the Monument: in the field of building Heritage conservation, investigation techniques, non-invasive and non-destructive analyses, represent a fundamental tool for physical, chemical, constructive and mechanical characterisation.

Making anamnesis and diagnosis an operational protocol and a method to support restoration projects means playing an active role in generating knowledge about the different components of the building.

At the same time, such a methodology enables to compare different methods of investigation, to propose and to verify different hypotheses.

In recent years, the development of increasingly powerful technologies for the creation of (i) digital twins [1]-[3], (ii) virtual reconstruction software [4], (iii) reality capture tools [5]-[7], (iv) 2D and 3D GIS software, and (v) BIM and HBIM [8]-[14] has given an enormous boost to the work of understanding, studying, conserving and safeguarding Architectural Cultural Heritage.

The aim of this work is to set up a Heritage Building Information Model (HBIM) system to facilitate the planning of diagnostic and restoration activities by bringing all archive information into a digital platform, accompanied by three-dimensional models that can be consulted, examined and, above all, updated.

The key to interpretation is eminently historical; a process in which the anamnesis of restoration is understood as a model of knowledge and a methodology of initial diagnosis to be conducted through history.

Without neglecting geometric, metric, and technical construction data, and with constant reference to technological and digital developments, to strive for the creation of an open source HBIM tool for the diagnosis of the state of preservation.

MATERIAL AND METHODS

Case study

The Cathedral, the main place of worship in the town of Troia (Foggia province), is one of the most valuable examples of Romanesque architecture in southern Italy [15], [16].

The construction history covers a period between the end of the 11th and the second half of the 13th century, from the foundation year (1093) to the construction of the rose window on the upper register of façade.

The history of the Cathedral's construction is complex. The plan, a latin cross with three naves, a transept and a single apse, was built in several phases on the foundations of a pre-existing church dedicated to Santa Maria (1083-1086).

The original layout, with three-naves separated by twelve columns in two rows and a 13th column on the side of the first column on the right was enriched by the construction of the left arm of the transept at the end of the 12th century. The project probably included the construction of the right arm, which was not built until the 18th century, during a restoration intervention. The third phase was characterised by the construction of the cross vault of the choir and the apsidal rose window in the presbytery area, while the last phase of construction, dating from

Figure 1. Main façade of Troia Cathedral © 2006, Nicola Masini.

the second half of the 13th century, was mainly concerned with the construction of the famous rose window in the upper register of the main façade (Figure 1), a magnificent example of Romanesque art, composed of eleven double columns, external and internal, mostly made of reused marble.

During the Renaissance and the 17th century, the history of the building witnessed a series of restoration necessary after the damage caused by seismic events (1456, 1627, 1731) [17]-[19].

The restoration works were entrusted to the Architect Federico Travaglini in 1857, as reported in Prot. n. 2677 of 25.05.189 Archive SABAP of Bari. In 1956, it was decided that the Cathedral would not be restored, considering the Monument as a document to be defended against any form of falsification [20]. Thus, the 19th century Cathedral gave way to an austere Apulian Romanesque façade.

The static condition of some parts of the Cathedral, including the rose window, continued to cause concern due to a recurrent lack of maintenance. During the twentieth century, the Cathedral has been interested by various restoration and consolidation works, followed by the most recent architectural and structural restoration of the façade and of the rose window in 2004, as reported in protocols drawn up between 1902 and 2002 and deposited in the SABAP Archive of Bari [21]-[53]; [54], see Figure 2.

Among the most illustrative events that marked the historical/constructive evolution of the Cathedral is the story of the original 17th century marble staircase with double ramp and balustrade.

In 1903, after a fierce debate involving both technical personalities and ordinary citizens, a new staircase in Castelluccio stone was built, designed by Arch. Adolfo Avena, then Superintendent of Monuments [21].

Figure 2. Photo of the rose window of the Cathedral, acquired by drone from N. Abate, 2022.

Figure 3. Extract of the registry of the archive sources consulted.

Not to be outdone were the numerous design proposals for freeing the thirteenth-century apse that located the sacristy rooms, which were only finally demolished in 1954 [25]. Also, the extensive plan of studies, experiments and works under the direction of Arch. N. Tomaiuoli, Dr. R. Gnisci and the Iconos Consortium, for the conservative restoration of the stone coverings of the main facade, carried out between the summer of '92 and the autumn of '95. After extensive experimentation with diagnostic tests and monitoring, an intervention project was defined consisting of cleaning, protection and consolidation, in order to ensure the preservation of the material and to counteract the onset of degradation phenomena [43]-[47].

Data acquisition

The creation of the HBIM digital tool for consulting the architectural artefact and related information was only the last phase of this work, which began with three different but fundamental activities:

(i) Acquisition of archival sources in order to reconstruct the history of the restoration and renovation work carried out on the Monument;

(ii) Acquisition of information about the diagnostic analyses previously carried out on the Monument (e.g., type of analysis, investigated area, used tools, results);

(iii) Acquisition of data useful for the creation of a digital twin, metrically correct and georeferenced, on which to operate with the HBIM method.

The anamnesis of previous interventions and diagnostic activities, in the context of the planning of restoration and diagnostic activities, is fundamental to: (i) understand the material evolution of the Monument over time (e.g., materials, additions, reconstructions), and (ii) have a dataset of diagnostic data already available on which to work. These operations were mainly bibliographic, archival and library collecting activities.

In particular, the set-up of the database was preceded by careful archival research in the archives of the Superintendence of Archaeology, Fine Arts and Landscape of the City of Bari.

All the available fund on the Troia Cathedral has been consulted and studied, and a register of sources has been drawn up. An extract from this register is shown below (Figure 3), which indicates for each document the archive location, the folders, the year, the protocol number, the type of document and the subject.

The archival funds, divided into four folders, cover a period from 1892 to 2008, with approximately two hundred textual, graphic and photographic documents consulted.

This consultation has made it possible to re-read the events on the artefact, to learn about the construction technique and the materials used in the historical work. The Cathedral is revealed as an emblematic palimpsest of theories and techniques in which it is possible to read and decipher history, in parallel with the theoretical and methodological evolution of the restoration field.

A critical reading of the documents has in fact revealed a history full of events, ideas, protests, projects, modifications that followed or opposed, case by case, restoration theories. A history can never be read and understood as a whole on the basis of the architectural text alone, but must be deepened, deciphered, confirmed and disavowed by the continuous and indispensable confrontation with history.

This activity was followed by the creation of weighted cards in which, for each element of the Monument involved in the previous activities, a card was created with links (keys) to other cards, in order to facilitate the search in a relational database.

The three-dimensional digital model was created using two different techniques in combined and integrated form:

(i) aerial photogrammetry using a DJI Matrice 210 v.2 with a 20MP camera Zenmuse X5S, to obtain the three-dimensional model of the roof and the areas inaccessible from the ground [55], [56]; (ii) laser scanner Trimble X-7 inside and outside the Cathedral of Troia [7], [57].

The survey activities were developed with the aim of obtaining a metrically correct three-dimensional model of the entire building (interior and exterior).

The operational phases that made up the organisation of the survey were: data acquisition; processing of the raw data; merging of the data into a single three-dimensional model; production of the final drawings.

(i) Aerial photogrammetry

Several flights were planned and carried out in different directions, taking into account the planimetric development of the area. The flights were carried out with nadir, oblique and detailed photos for the upper part of the naves and the rose window on the façade, in order to obtain general and detailed elements of the entire structure.

F.	PROTOCOL	DATE	TIPE	SUBJECT
1	Subject n. 7	16.01.1892	Dossier	Application to the Ministry of P.I. for the restoration of the steps and restoration of the facades of the Trojan Cathedral
1	2677	25.05.1893	Dossier	Cathedral of Troia. Report
1	2677	25.03.1893	Drawing	Elevation of main access stairs
1	14119-3826	15.06.1893	Dossier	Work and studies for the Cathedral of Troia
1	1342	09.07.1898	Dossier	List of some works to be carried out in the Cathedral of Troia
1	7502	1899	Drawing	Hand-drawn plan
1	2603/MF	21.02.1900	Single document	Notes from the trip to Troia for the restoration work on the Cathedral
1	Annex n. 4	14.09.1900	Minute	Estimate for rainwater drainage works and transformation of the existing access stairs
1	1984	n.d.	Minute	Estimate for the restoration of the roofs, the front frame, the N-W corner and the replacement of the main access stairs
1	1534	23.01.1903	Single document	Troia - Cathedral. Urgent repair measures
1	3604	02.1903	Photo	Photo of the main facade
1	438	13.02.1903	Minute	Urgent work at Troia Cathedral
2	Year XL - N. 209	11.09.1906	Journal article	The defence of Troia Cathedral
2	n. 3	10.04.1910	Single document	Report on the economic work carried out on the external wall of Troia Cathedral
2	Annex n. 2	17.11.1910	Dossier	Report on the restoration project and a new stairs at Troia Cathedral
2	Annex n. 2	17.11.1910	Dossier	Test Certificate
2	Annex n. 2	17.11.1910	Dossier	Test visit report
2	9697	1914	Single document	Plan of the Cathedral of the city of Troia
2	7635	1914	Drawing	Floor plan of the Cathedral of the city of Troia
2	590-274	03.06.1918	Single document	Letter
2	631-324	10.08.1921	Free sheets	Letter

The flight for the general survey of the Monument, with nadir and oblique (70°) photos, was carried out using the DJI GS PRO automatic flight application, supplied by the manufacturer of the DJI Matrice 210v2 [58], with a Zenmuse X5S camera [59]. The application allows the creation of an automatic flight plan by setting the recording time, the lateral and frontal overlap between the photos and the ground resolution (GSD - Ground Sample Distance). The flight was carried out to achieve a ground resolution (roof cover) of 0.2 cm/pixel. The total number of images acquired in this way was 363.

The vertical elements were acquired by manual flight operations. The operations resulted in approximately 100 photographs, taken in sequence with an 80% overlap pair of photographs, covering the area of the central rose window and the aisles.

In order to capture the architectural artefact in its entirety, it was also necessary to carry out a photographic campaign from the ground using a Canon EOS D1100 reflex camera [60]. The photographs were taken at three different heights in order to frame each part of the wall surface and to avoid gaps in the final models. The collection of metric and geometric data, carried out in the field using traditional architectural surveying methods and tools, allowed the model to be correctly oriented and scaled. Approximately 891 high resolution photographs were taken for this process.

The photogrammetric processing involved the use of the entire photographic data set acquired. 1341 images were processed, of which 1341 were perfectly oriented, resulting in a cloud of 60,090,971 points and a model with 2,836,974 faces and 1,420,537 vertices.

The software used to generate the photogrammetric processing was 3DF Zephyr (Figure 4 and Figure 5).

The processing included several steps: general orientation of the acquired photographs; georeferencing using GCPs (Ground Control Points); refinement of the result to obtain a dense point cloud; cleaning of the point cloud obtained through classification and filtering operations by confidence (reliability of the point with respect to processing); creation of the mesh model (triangulation between points to create surfaces); creation of the textured model and, finally, exporting the data.

The model thus created made it possible to extract orthophotos, photoplans, a dense point cloud, a mesh model and a textured model.

Finally, the perfectly textured metric model was processed, which made it possible to graphically represent different types of information (degradation, forms of alteration, crack framework). The results obtained made it possible to reconstruct the cognitive framework of the physical, constructive and mechanical aspects to be correlated with the historical study and the evaluation of the state of degradation (Figure 6).

In order to obtain a complete 3D model with no gaps, the point cloud acquired by laser scanner was integrated with the point cloud acquired by means of terrestrial and aerial proximity photogrammetry using the special functions of the 3DF Zephyr cloud-to-cloud orientation software, which allow the orientation and subsequent refinement between two-point clouds by recognising the morphology of the point clouds themselves (Figure 7).

(ii) Interior and Exterior Laser Scanner Survey

A Trimble X-7 laser scanner [61] was used for the acquisition of the exterior curtains and interior areas of the Monument.
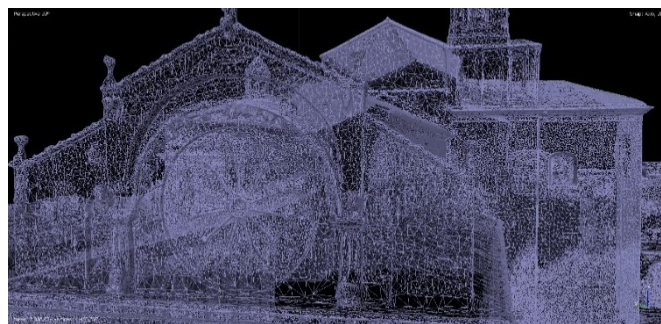

Figure 4. Drone acquisition: mesh model, zoom of the rose window of the main elevation on Regina Margherita Street.

Figure 5. Drone acquisition: textured model, zoom of the rose window of the main elevation on Regina Margherita Street.

Figure 6. Textured 3D model obtained by terrestrial and aerial drone photogrammetry.
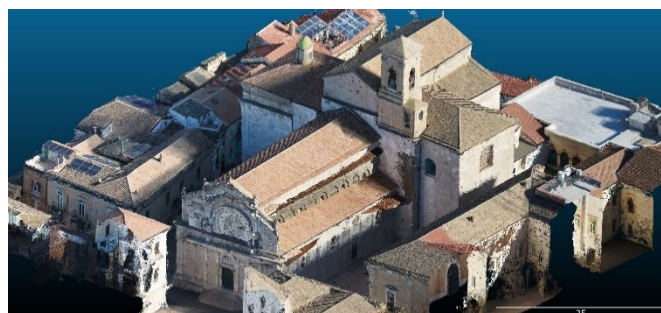

Figure 7. Integration of the point cloud acquired by laser scanner.

For the survey of the exterior areas, 16 acquisition stations were carried out, the result of which was a high-density point cloud (11 million points per scan) with an average error of 1.7 mm, an average overlap of 60 per cent and an average consistency of 98 per cent (Figure 8).

For the survey of the interior spaces, on the other hand, 30 stations were acquired, connected and oriented with each other,
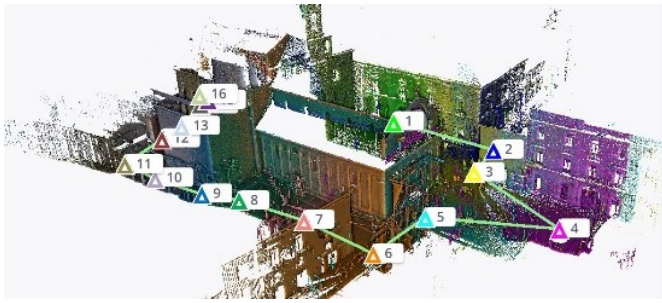
Figure 8. Laser scanner acquisition of the exterior: 16 stations with instrument positioning at predefined points in the survey area.
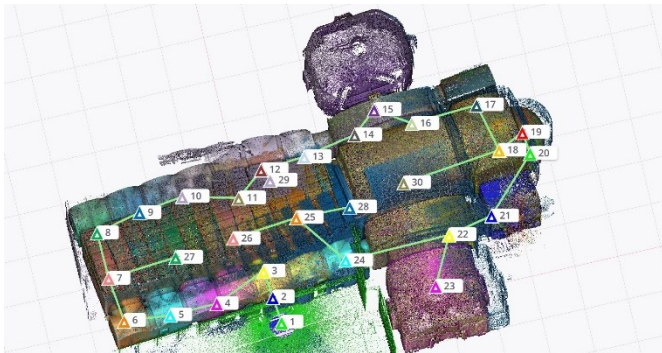

Figure 9. Laser scanning of the interior: 30 stations with total coverage of the interior of the church.
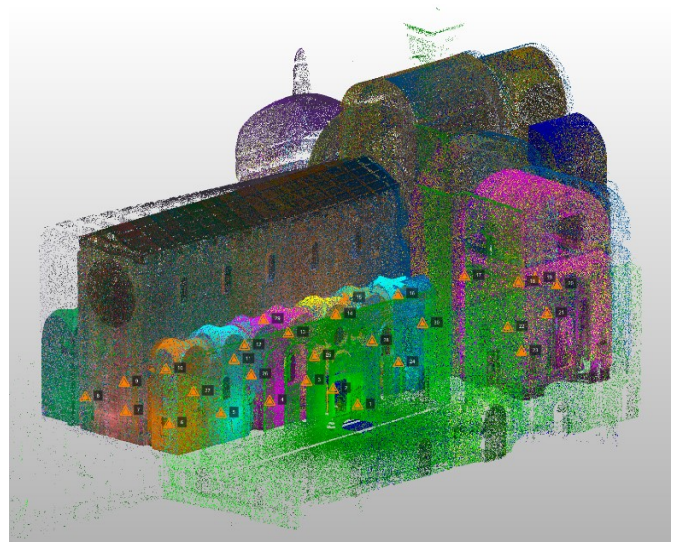

Figure 10. Laser scanner acquisition of the interior: high-density point cloud.
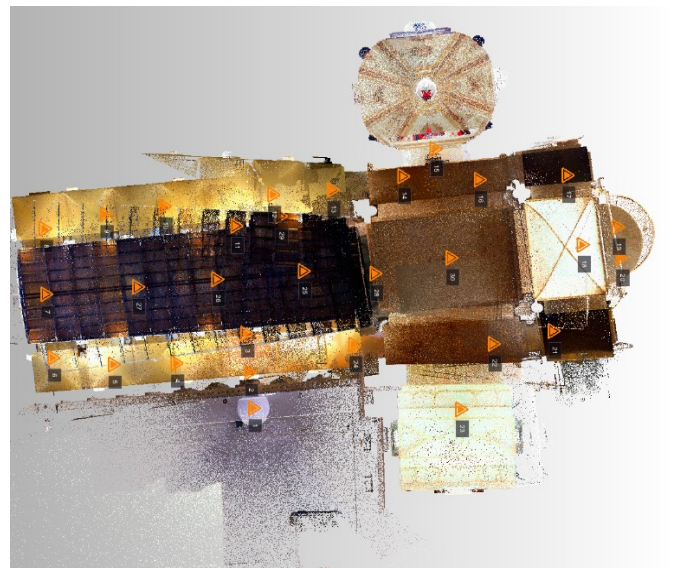

Figure 11. Laser scanner acquisition of the interior: accurate reconstruction of interiors – view 1.

Figure 12. Laser scanner acquisition of the interior: accurate reconstruction of interiors – view 2.

in order to obtain a total and complete mapping of the Monument (Figure 9).

In the subsequent processing phase, each individual scan was further checked and optimised. Finally, all scan stations were re-oriented (recorded) using Trimble Real Work software.

The result of the registration was a point cloud model with a millimetre margin of error.

Registration was followed by the final data processing phase, which led to the creation of the geometric model (mesh).

This is a model in which point clouds are transformed into surfaces to make the model itself more intuitively understandable and manageable with 3D modelling software (Figure 10 to Figure 12).

From these scans, the model was processed, which, following georeferencing by means of GNSS points acquired in RTK mode, was used to create orthophotos exportable in CAD and extract the corresponding graphical drawings (plans, elevations, sections).

Towards the creation of the HBIM digital tool

Once all the data relating to the cards and the three-dimensional model were obtained, the open-source 3D modelling software Blender was used to create a prototype of the rose window HBIM (Figure 13), with the addition of following add-ons: (i) yEd graph, and (ii) Extended Matrix palette v.1.2.

In this way, it was possible to associate the collected information with each single element modelled in three dimensions and to create a network of connections between the different elements (Figure 14).

The combination of databases and reference models makes it possible to analyse and compare data and interventions in order to obtain reliable projects, programmes and actions.

Such a digital data synthesis tool can be a fundamental aid for the definition of restoration interventions, as it would guarantee an easy retrieval of general and specific information.

The systematisation, digitalisation and availability of all information is a fundamental tool for the dissemination of knowledge, as well as an executive guarantee of correct interventions on Monuments.
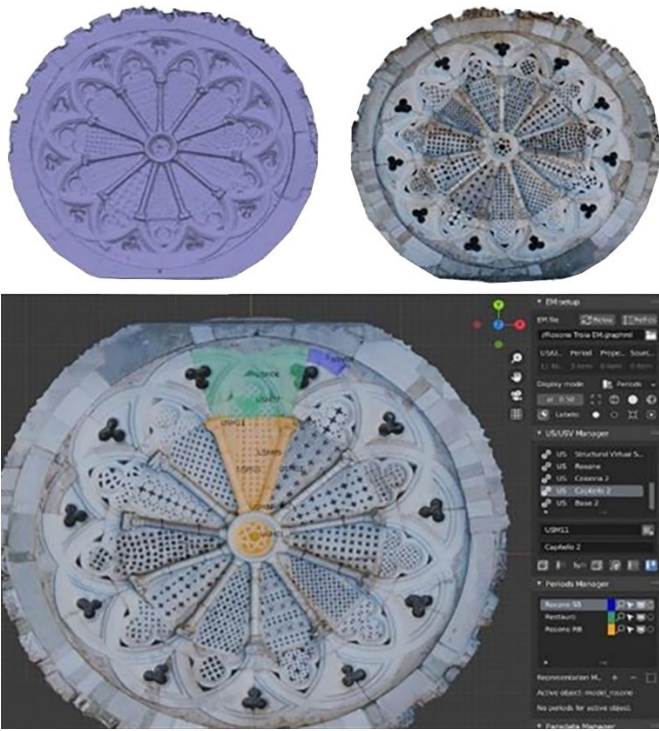
Figure 13. Three-dimensional model of the rose window of the Cathedral and HBIM preliminary operations.

Bringing together different types of data in a single reference tool can allow a complete anamnesis and diagnosis of the Heritage, avoiding incorrect design choices due to the lack of an adequate cognitive substrate.

The structuring of digital libraries that can be implemented with continuously updated data represents an exceptional tool for restoration work, acting as a decision support tool that prevents the dispersion of data to be interpreted and compared. The proposed dataset would allow data to be analytically interpreted and processed through a database that qualitatively and quantitatively integrates different types of investigation methods, creating links between results obtained with different tools.fg
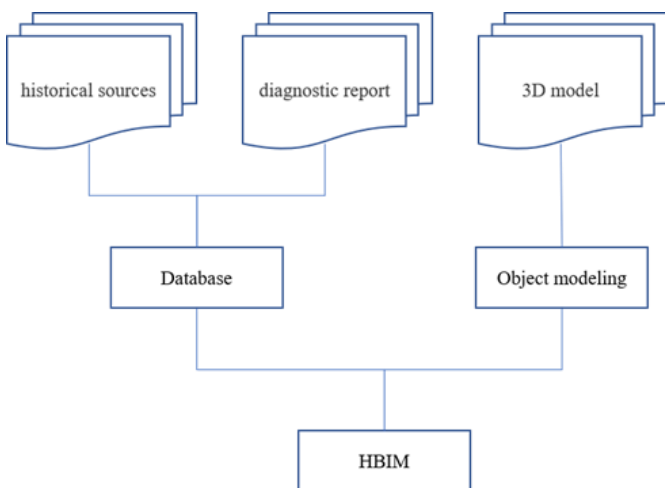

Figure 14. Flowchart.

RESULTS

The result of this approach was the first, preliminary creation of an easy tool for questioning the evolution of the Monument alignand the studies carried out on it. In particular, this tool proved to be an easy way to find information in a complex Monument such as that of the Cathedral of Troia.

The speed of information retrieval along all the elements implemented within HBIM makes it extremely easy to approach the planning of new analysis and restoration campaigns, avoiding the redundancy of activities (e.g., repeating analyses already carried out in the past due to the impossibility of retrieving the data) or the misunderstanding of the built due to lack of knowledge (e.g., wrong interpretation of the zones yet restored).

The HBIM model would, in fact, make it possible to relate a considerable amount of heterogeneous data by means of IDs and
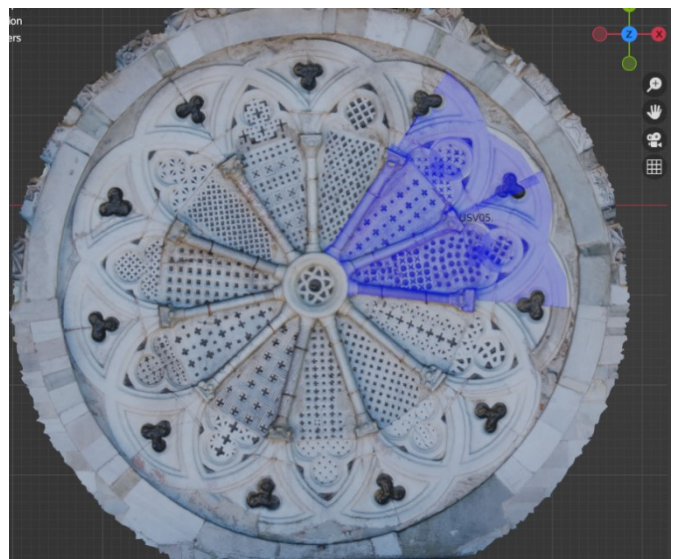

Figure 15. HBIM model of the rose window of the Cathedral with the marked arched ribworks between column n. 5 and column n. 3 (sample n. 526).
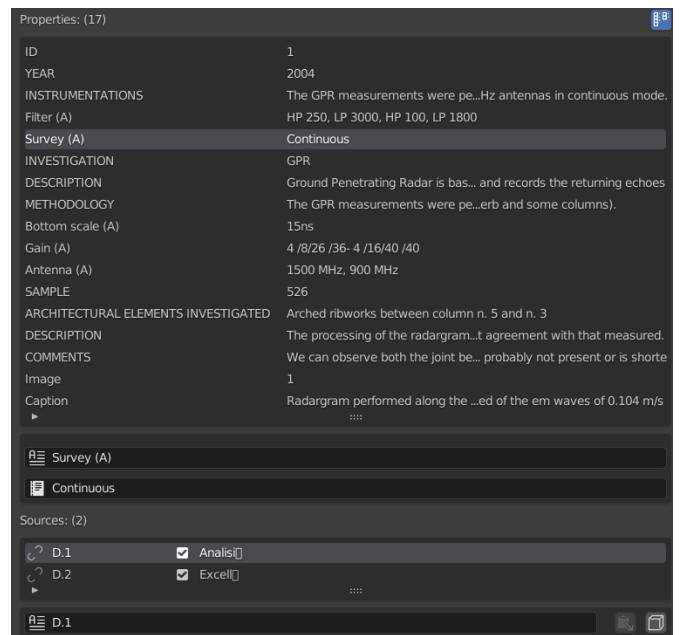

Figure 16. Associated GPR survey information conducted on the arched ribworks between column n. 5 and column n. 3 (sample n. 526).

key elements such as the type of investigation carried out, the architectural element investigated, the construction material, etc.

Each related table would talk about the different kind of surveys, indicating their type, the methodology of execution, the staff involved, and the results obtained (Figure 15 and Figure 16).

As can be seen in this arch between two columns of the rose window, in which we read the GPR surveys conducted in 2004.

CONCLUSIONS

A digital data synthesis tool can be an essential tool for research and for defining restoration interventions. It would facilitate the easy retrieval of both general and specific information related to the object of study or intervention.

A digital tool designed in this way supports knowledge, analysis and interventions planning based on the interoperability between the building's history and its current diagnosis, guaranteeing a double result.

On the one hand, the design of an integrated system, that makes it possible to manage and use all information known about the Monument, based on historical and collected data in the field.

On the other hand, the possibility of implementing and modifying the same information model in real time with new data obtained from experimental surveys, monitoring, and interventions in progress.

The availability of this anthology of knowledge will allow to understand the evolution of restorations practices on a case-by-case basis, to review past initiatives, and to provide direction for future interventions. This approach will help to optimize resources by avoiding unnecessary ones.

This is particularly useful for a complex Monument such as that of Troia, since the Troia's Cathedral is literally a palimpsest of practices and techniques over an unprecedented period: from the mid-nineteenth century through the entire twentieth century, to the early 2000s.

The future perspectives are therefore aimed at implementing the database and the model of the entire Cathedral, with the anamnestic contents of the archives and with the results of the new diagnostic investigations, currently underway, defined with the historical methodological approach presented.

The methodology for diagnosing the state of conservation of the Architectural Heritage using the HBIM digital tool will therefore continue to be the subject of study, research and experimentation in order to achieve validation.

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ARCHIVE SABAP (Superintendence of Archaeology, Fine Arts and Landscape) OF BARI. POSITION: FG LVIII

Folder n. 1 (1892-1950):
[21] Annex n. 4 of 09.03.1902
[22] Article of 11.09.1906
[23] Annex n. 2 of 17.11.1910
[24] Prot. n. 1388 of 04.08.1927
[25] Expertise of 16.11.1928
[26] Prot. n. 1738 of 20.08.1948
[27] Estimate of 16.11.1928
[28] Report of 17.02.1937
[29] Prot. n. 1854 of 17.03.1938
[30] Prot. n. 1232 of 13.09.1946
[31] Expertise of 15.06.1948
[32] Expertise of 16.09.1958
[33] Expertise n. 33 of 14.05.1958

Folder n. 2 (1950-2000):
[34] Prot. n. 5017 of 03.12.1965
[35] Dossier of 06.07.1968
[36] Prot. n. 7976 of 14.07.1975
[37] Prot. n. 5066 of 19.06.1978
[38] Prot. n. 3066 of 09.02.1988
[39] Prot. n. 2603/MF of 12.02.1988
[40] Prot. n. 7502 of 21.05.1991
[41] Prot. n. 12570 of 23.08.1991
[42] Prot. n. 12664 of 27.08.1991
[43] Prot. n. 2919 of 08.02.1996
[44] Prot. n. 020202 of 28.08.1997

Folder n. 3 (2001-2002):
[45] Prot. n. 010081 of 11.04.2001
[46] Prot. n. 010521 of 12.04.2002

Folder n. 4 (2003-2008):
[47] Prot. n. 001178 of 15.01.2003
[48] Prot. n. 6667 of 18.07.2003
[49] Prot. n. 8985 of 30.09.2005

[50] Prot. n. 08971 of 18.10.2005
[51] Testing of 26.07.2007
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