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FROM SURVEY TO ANALYSIS FOR CULTURAL HERITAGE MANAGEMENT: A NEW PROPOSAL FOR DATABASE DESIGN IN BIM

N. Bruno

XXX ciclo di dottorato
Università degli Studi di Parma, Dipartimento di Ingegneria e Architettura, Parco Area delle Scienze 181A, 43124, Parma, Italy – nazarena.bruno@studenti.unipr.it

KEY WORDS: HBIM, Cultural Heritage, Survey, Metadata, 3D Modelling, Database design

ABSTRACT:

The need to safeguard and preserve Cultural Heritage (CH) is increasing and especially in Italy, where the amount of historical buildings is considerable, having efficient and standardized processes of CH management and conservation becomes strategic. At the time being, there are no tools capable of fulfilling all the specific functions required by Cultural Heritage documentation and, due to the complexity of historical assets, there are no solution as flexible and customizable as CH specific needs require. Nevertheless, BIM methodology can represent the most effective solution, on condition that proper methodologies, tools and functions are made available.

The thesis work, presented here, aims to give a concrete answer to the lack of specific tools tailored for Cultural Heritage documentation. It addresses the implementation of a BIM system aimed at maintenance, conservation and restoration of Cultural Heritage. BIM methodology is addressed from a geomatics perspective, giving on the one hand a contribution especially to survey and database implementation, and, on the other hand, interfacing with other disciplines actors, in order to collaborate and share objectives and strategies.

In particular, a specifically designed database was implemented, where all data about the historical building can be stored. A tailored database is necessary to organize historical data that generally are not standardized, have a complex structure and are fuzzy in their description.

The application was implemented with the specific aim of providing tools also for non- AEC experts: it gives user-friendly graphical interfaces to access the data and makes available tools for data entry, element modelling, attribute query and thematic mapping.

It can be integrated into the main commercial BIM software (at the moment the experimentation has been limited to Revit) or accessed via web. One of the main goals was not to be bounded to a specific software and to make the system usable on a larger scale.

Database design and system usability have been the most investigated topics, since to date there are still few studies concerning the organization of semantic data, system usability and data sharing. Nevertheless, all the aspects concerning the application of BIM process to historical assets (level of accuracy, compliance with the surveyed data, parameterization of complex elements, management of deformations and irregularities, integration of pre-existing databases) have been addressed, in order to define a complete methodology.

The Cathedral of Parma was chosen as case study to test the methodology, but the system was implemented to be flexible and customizable, in order to apply this methodology to a wide range of historical assets.

1. INTRODUCTION

In recent years, there has been an increasing diffusion of the BIM (Building Information Modelling) methodology, mainly thanks to the introduction of regulations and standards that impose or at least regulate its use. Italy, thanks to the recent publication of the new UNI 11337:2017 standard, is also moving towards a progressive adoption of the BIM in public contracts.

BIM methodology allows managing, in a coherent and coordinated way, all phases of a building lifecycle and is therefore not simply a design tool, but can also be applied to existing buildings.

The use of BIM for documentation and management of historical buildings would certainly have positive effects. In fact, as shown by literature, BIM greatly simplifies the management of the time factor in building documentation. It makes it possible to handle coherent and coordinated data relating to different time phases, to highlight and separate the different construction phases, as well as to keep track of all the performed or scheduled interventions. It also provides a single access point for all the available data, constituting a sort of unique and searchable archive.

Especially in Italy, where the amount of historical buildings is considerable, having efficient and standardized processes of CH management and conservation becomes strategic.

BIM represents an effective tool for supporting scheduled maintenance and conservation activities, which are an increasing important instrument for safeguard and conservation of Cultural Heritage. Preventing the onset of risk and damage situations helps to limit the invasiveness of restoration interventions and avoid situations of danger for the asset.

Nevertheless, currently BIM is principally associated to new construction works and only in the last years its use is spreading to existing buildings too (Volk et al., 2014), while in the field of Cultural Heritage, the use of BIM is very limited and remains the prerogative of universities and research institutes (De Luca et al., 2011; Fassi et al., 2015; Dore et al., 2015).

The reasons for this disparity can be traced back to the difficulties involved in setting up a BIM of historic buildings. There are not specific regulations and, in general, there is not yet a shared awareness of the importance of BIM in Cultural

Heritage and, therefore, there is no commitment to act in this regard by providing *ad hoc* solutions for cultural assets.

Problems arise w.r.t. geometric modelling, especially of irregularities that do not fit well with the parametric modelling typical of BIM (Eastman et al., 2008; Garagnani et al., 2013). At the same time, information organization pays the lack of as flexible and customizable solution as required by the heterogeneous and difficult to standardize structure of historical data.

Another non-trivial aspect is the multi-temporality of information and the need to have a system usable for diachronic analyses. Historical data are, in fact, by their nature multi-temporal and, in addition, conservation is a continuous activity that requires constant updating of information and continuous collection and processing of different data.

Last but not least, an interdisciplinary approach is mandatory to well know the building and translate it correctly in a virtual model. The operators who work in Cultural Heritage field are not used to work with databases, information systems, 3D models etc., so a system tailored for CH management should be user-friendly and easy to use/learn even for non-experts (Fassi et al., 2015).

Nevertheless, BIM should represent the most natural and modern approach to historical assets management, providing many advantages such as documentation over time, management of different construction phases (Stefani et al., 2010), support for structural analysis (Dore et al., 2015; Crespi et al., 2015), unique database for all data about the building (Fai et al., 2011), support for ordinary maintenance programs (Fassi et al., 2015), support for Augmented Reality applications and web sharing (Fassi et al., 2015) and so on. In this context, the implementation of a BIM for historical building documentation can be a big challenge but, at the same time, a technological improvement that enables a better and deeper knowledge of these assets.

The thesis project led to the realization of a Historic BIM system for the Parma Cathedral aimed at restoration and maintenance of historic buildings. The implemented system has been conceived to give a concrete answer to the lack of tailored tools for Cultural Heritage documentation.

The application, thanks to a specific database, allows storing and querying the data necessary for the description of historical buildings. A tailored database is necessary to organize historical data that generally are not standardized, have a complex structure and are fuzzy in their description.

It can be integrated into the main commercial BIM software (at the moment the experimentation has been limited to Autodesk Revit (Autodesk, 2018)) or accessed via web.

This thesis addressed the BIM methodology from a geomatics perspective, giving a contribution especially to survey, modelling and database design.

Database design and system usability, in particular, have been the most investigated aspects. In fact, if the themes related to surveying and modelling are widely investigated in literature, there are still few studies concerning the organization of semantic data, system usability and data sharing.

To test the proposed methodology, the Cathedral of Parma was chosen as case study, but the system can be applied to other similar historical buildings.

2. METHODOLOGY

The first phase of the work involved the analysis of the regulatory requirements and specific needs that the building chosen as case study presents. Then, the acquisition of both geometric and semantic data, through instrumental survey and documentary and normative analysis, were performed. On the basis of the data acquired, working in an integrated way between the need for modelling, documentation, accuracy, data manageability and system usability, the three-dimensional model has been created and the information system has been implemented.

The HBIM has been conceived as an information system on the architectural scale and as an integrated process of survey & data acquisition, 3D modelling and database design & data entry (Figure 1).

Especially in the cultural heritage field, the creation of a BIM is not a linear process, but an integrated and circular one. Survey, modelling and database design influence each other. For example, the accuracy with which the survey is performed and the achieved level of knowledge of the object influence the quality of the model (in terms of accuracy and adherence to reality) and of the database (in terms of organization of information and data stored).

For this reason, designing these components independently leads to inconsistencies and reduces the effectiveness of the global system.

For each of the three phases, the main features and problems have been identified, trying to give an original contribution to the solution of some outstanding issues.

Today there are different consolidated techniques available in each of these fields, but in order to analyse historical assets, not all the methodologies are suitable. In the work, all the three issues have been addressed, in order to define a complete methodology.

As far as the survey is concerned, in such complex contexts, geometric and spatial data are generally acquired through integrated surveys, increasing the available products and overcoming the specific limitations of each technique. Literature references are many (Castagnetti et al., 2017; Fassi et al., 2010; Remondino, 2011) and the acquisition techniques are well-established. On the contrary, no specific references are about the integration of these acquired data in a BIM environment, nor about their exploitation to certify the quality of the BIM model.

Likewise, 3D modelling techniques and commercial software that can be used to represent a building are well-known and discussed by literature (Achille et al., 2007; Guidi et al., 2009). As for the survey, even for modelling, it is not yet adequately defined how certify and validate BIM model quality and accuracy, which are influenced by the quality of the data surveyed and the modelling operations carried out.

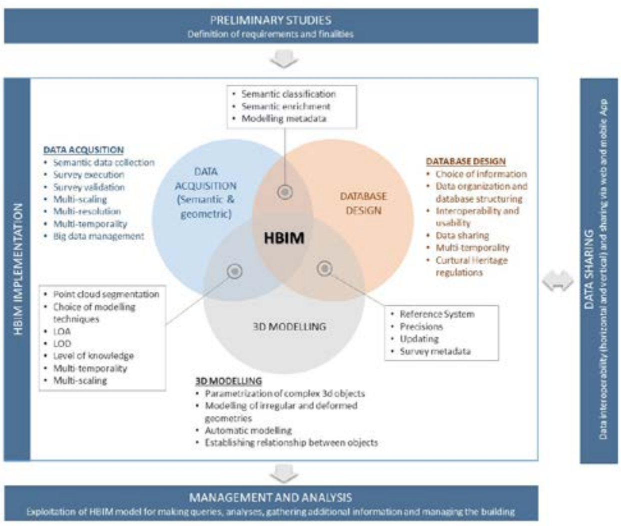

Figure 1_Methodology overview.

On the contrary, semantic data acquisition and their organization in a relational database are less investigated topics, with only a few literature references. The main focus was therefore on the database design phase and data usability, since these issues have still many open research fields and suffer from the difficulties of identifying a standard methodology adaptable to different historical contexts and at the same time able to ensure simple and dynamic access to information.

3. THE CASE STUDY: PARMA CATHEDRAL

Figure 2_Parma Cathedral example views.

The history of Parma Cathedral has still some unclear aspects, in particular with regard to its construction dates. It is now accepted opinion (Blasi et al., 2006) that its construction started in the second half of the XI century and was completed under the direction of Matilde of Canossa at the beginning of the XII century.

During its lifetime, the church has been subject to changes, additions, damages and repair works. The most important event that influenced the cathedral conformation was the strong 1117 earthquake, which caused the collapse of many parts.

Since that event, the history of works and restorations has been long and lasting. At present, the building suffers structural and material problems. Structural problems have always affected the cathedral, in particular the central nave and the crypt. They are principally due to the high thrusts of the vaults of the central nave and the weight of the dome, which cause a considerable out-of-plumb in the side walls and the subsidence of the structures under the dome.

Material decay affects instead principally stones and decorative elements in the façades. Externally, the cathedral is chiefly built of bricks, although, as evidenced by some plaster remains, it had to be entirely plastered. Lesenes and corners are instead made of stone, especially sandstone and limestone, which are very sensitive to atmospheric agents, and tend to delaminate and crumble.

As continuous restoration and maintenance works are required, its complexity, size and characteristics, the Cathedral offers a significant sample of challenges and issues to which refer and is a suitable case study to implement the methodology proposed.

4. THE INTEGRATED SURVEY

The survey has been designed in order to be integrated, multi-resolution and scalable in time. Integration allows indeed overcoming the specific limitations of each technique, having more complete results (Bianchi et al., 2016); multiresolution is useful to manage the huge amount of data that generally comes from such survey and to have, at the same time, a correct overview and an adequate level of detail; finally, scalability ensures the progressive survey implementation in time and the supports for monitoring purposes, by comparing data acquired in different epochs.

The survey, even in complex and articulated contexts such as the one under investigation, from the point of view of execution, follows the methodology now consolidated, obviously declined on the specificity of the object under examination. In particular, with regard to Parma Cathedral, the main difficulties have been related to the cathedral volumetric features and to the surrounding context: occlusions, different levels of detail, façade height, narrow streets around the Cathedral made acquisition phases difficult.

From a methodological point of view, the thesis addressed, in addition, the interaction between survey and BIM: how the survey data and metadata can be entered into the database to document and validate the operations carried out (see paragraph 6.1).

As far as the outputs are concerned, restitution was planned for a nominal average scale of 1:50, reserving the 1:100 scale for less accessible areas and 1:20 for some peculiar details. In addition to the 3D model for HBIM implementation, particular attention was payed to material degradation representation. To this aim, the realization of orthophotos of the external façades was mandatory and the possibility to associate them to the 3D model has been foreseen.

4.1 Topographic survey

In order to refer the integrated survey to a stable reference network, identifiable station points have been marked all around and inside the Cathedral. As shown in Figure 3, twenty-two stations were materialized and surveyed.

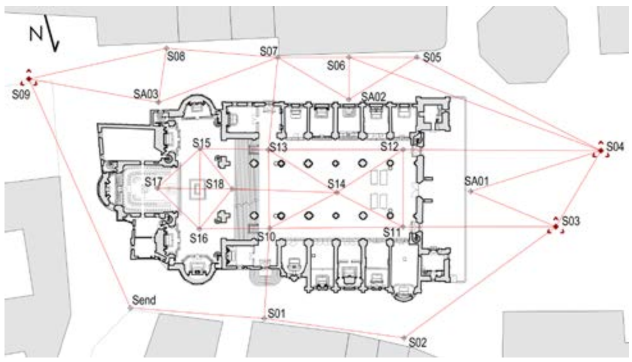

Figure 3_Topographical network of traverses.

The Topcon Image Station IS2 total station was used and the observations were adjusted through rigorous least squares minimization with the software Calge (Forlani et al., 1986). The adjustment provided a mean accuracy of ca. 2.1 mm, which can be considered acceptable for most modelling and monitoring activities if very high precisions are not required.

The topographical network was georeferenced with a GPS survey of three vertices (vertices S03, S04 and S09), placed in the two squares at the opposite corners of the cathedral (Piazza Duomo and Piazzale S. Giovanni).The GPS coordinates were obtained through 4 hours static session with respect to a station of the CORS (Continuous Operation Reference Station) network Netgeo about 9 km away and then transformed in a local Cartesian reference system with origin in the midpoint between the GPS stations.

4.2 Laser scanner survey

As said before, the terrestrial laser scanner (TLS) survey was made with a multi-resolution approach, so two different scan phases have been designed: a global survey and a detailed survey. The global survey aimed at generally document the cathedral, having a complete survey of its main volumes.
19 scans were performed in correspondence of the topographic network points. In the nave, in the transept and in the choir, the scans were acquired with an average resolution of 6÷7 mm on the object. In the presbytery (S15, S16, S17, S18), the resolution was instead equal to 2÷3 mm on the object, due to the high level of detail in the presbytery area.
The detailed survey has been designed as a local survey, in order to increase the resolution (average distance between the points equal or less than 5 mm) in the most complex and detailed areas. The methodology was tested in some areas, such as the loggias in the apses.
All the scans were acquired with the Leica Geosystem C10 scan station and were registered in Cyclone, using as reference the known coordinates dataset obtained from the topographic survey
The registration provided satisfying results, with an average residual of 2 mm and a standard deviation of 1 mm, in accordance with the instrument nominal precision.

Figure 4_The complete point cloud after registration.

4.3 Photogrammetric survey

In the Parma Cathedral survey, photogrammetry provides an essential integration to TLS. Image acquisition was far from simple, since the presence of many occlusions and the narrowness of the streets around the Cathedral that dictates oblique imaging in order to frame the upper part of the façades, with large variations in image scale from the base to the top of the façade. This in turn cause a progressive decrease of accuracy and resolution from the lower to the upper parts.
An Unmanned Aerial System (UAS) would provide a much better imaging geometry and would be beneficial for detection of the areas not visible from the ground level, with reduction of occlusions and for the roofs survey. However, at this time, it has not yet been possible for issues related to authorization to fly in the city centre.
Therefore, for the moment, only images from ground have been taken, suitable to model the building up to the level of the lower eave (side chapels and apses).
A Nikon D3x (resolution 6048x4032 pixel, pixel size 6 µm) with 35 mm optics has been used. The photogrammetric block was designed to reach a precision adequate for 1:50 representation scale (σ = 1 cm).
The image sequence consisted of 326 images that were oriented automatically using Agisoft Photoscan. High accuracy image orientation with a generic pair pre-selection modality has been chosen. To define the reference system of the restitution and orient absolutely the image block, 15 well-distributed Ground Control Points (GCP) were selected on natural features (e.g. edges, corner, surface discontinuities, etc.) since, for the moment, the Cathedral Fabbriceria did not granted permission the installation of permanent targets to the Cathedral walls.
The use of natural points makes collimation more difficult and point identification less precise. This is true despite a GSD of the order of 3 mm, as the edges of architectural elements are always worn and corroded. For this reason, in order to improve the accuracy of the photogrammetric survey, using artificial targets is desirable. Therefore, in accordance with the drone survey campaign, the authorization for installation will be requested again.
The lack of targets on the walls of the Cathedral caused great difficulties also for the validation of the photogrammetric survey. Two different procedures have been applied: the analysis of the residuals on some check points located on natural features and a comparison between the photogrammetric DSM and the laser scanner point cloud.

- Check points validation: 33 natural points have been acquired by topographical measurements and used as check points. From the residual stats (Table 1), it is possible to note that the solution is apparently a little worse than the accuracy estimated in the block design phase (1 cm), with an RMS of 16.1 mm. On the contrary, the maximum error values are rather high. Given the difficulties of collimation mentioned above, it is possible that these high values are due to errors of collimation, either during the topographical survey or the image point identification.

	XYZ Error [mm]	X error [mm]	Y error [mm]	Z error [mm]
RMS	16.1	9.2	9.7	9.0
Mean	14.9	2.0	0.8	2.3
Std. dev.	6.2	8.9	9.7	8.7
Max val	26.8	17.4	23.9	16.4
Min val	0.7	-14.6	-15.6	-20.9

Table 1_Check points residuals.

- DSM comparison: the second validation procedure concerns the comparison between the DSM obtained from the photogrammetric survey and the laser scanner point cloud. The outcomes of this comparison are shown in Figure 5.

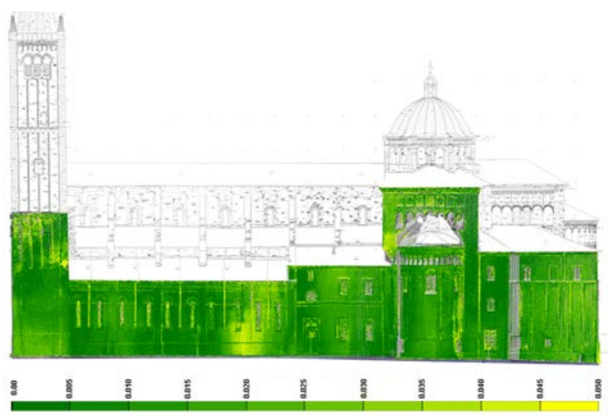

Figure 5_Map of displacement [m] between DSM and laser scanner point cloud.

The analysis of the discrepancies histogram shows that 71 % of the points distances are lower than 16 mm (1σ) and 94 % of the whole dataset is under 32 mm (2σ) of displacement. The results tend to confirm the pointwise indication gathered by the check point analysis.

At the end of the structure from motion procedure, with the same software package, the DSM of the exterior side of the Cathedral was obtained. In addition, the high-resolution orthophoto (GSD 3 mm) were produced (Figure 6).

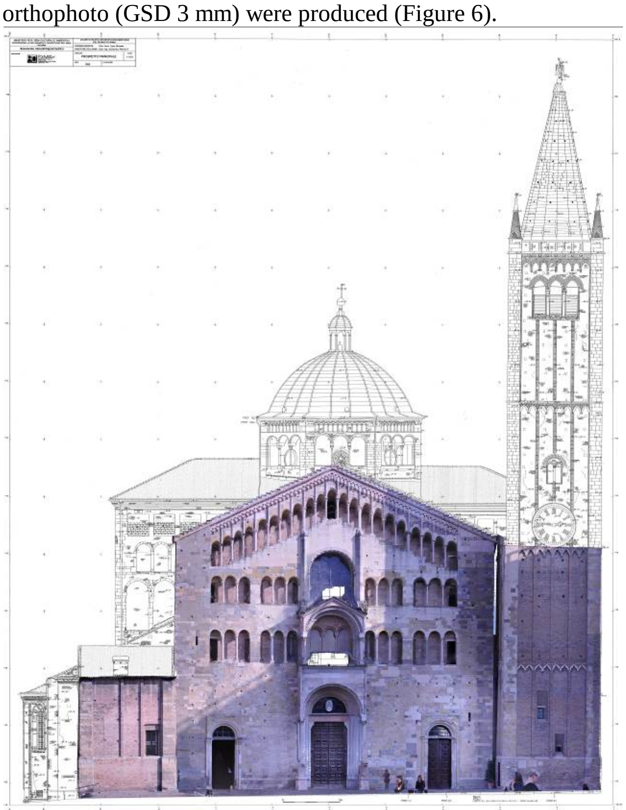

Figure 6_Orthophoto of the Cathedral main façade overlapped to the drawings of the photogrammetric survey made by FOART in 1989.

5. THE 3D MODELLING

Historical buildings are irregular and characterized by heterogeneous and complex shapes. For this reason, the modelling methodology is still an open question and copes with the difficulty to retrace the correct shape of the object (Barazzetti et al. 2015).

The advantages of parametric modelling (both generative and object oriented) are evident: it speeds up modelling phase allowing the user to replicate and modify object dimensions by changing the value of some parameters.

In CH field, one of the most crucial aspects in implementing an HBIM is the lack of libraries of historical architectural elements (Apollonio et al., 2012). Nevertheless, parametric object modelling is not flexible and imposes many constraints that limit the accuracy of the model and its conformity to surveyed data. Especially in the field of cultural assets, this causes many problems and limitations on the correctness of the modelling of objects.

Working on historical buildings, the attempts to create parametric models often is not sufficient and a model based on families of pre-modelled elements hardly fits the actual form of the object.

In modelling irregularities, there are several class of problem to take into account. First of all, the capabilities of the available software. BIM tools are conceived for new construction and, generally, do not allow "irregularities" such as out of plumb of the walls, not perfect planarity, off axis lines etc. All these irregularities can be solved more easily with direct modelling tools, but this causes interoperability problems. In addition, creating a high accurate model results in very long modelling times and unmanageable size models.

Literature references on this topic are many (Tommasi et al, 2016; Dore et al., 2015; Bitelli et al., 2017, Barazzetti et al., 2015) but the modelling of irregularities is still an open issue. The representation scale and the purpose of the model are key factor to determine the adequate level of detail, even to avoid having totally unmanageable model unusable for requested analyses (Donato et al., 2017). The representation scale entails a defined tolerance and therefore, according to it, the admissible level of accuracy is defined.

Integration of different modelling techniques using mesh surfaces too could be a feasible solution, but cause interoperability problems (Tommasi et al., 2016). It is therefore author's opinion that to correctly merge in a unique model elements modelled with different techniques and with different software the new direction of development must look at concrete interoperability; an interoperability that allows data exchange (without loss of information) and thematic data association.

5.1 The adopted strategies for irregular shape modelling

In this case study, a hybrid solution that combines parametric models, direct modelling into BIM environment and meshes has been proposed, trying to overcome interoperability problems using links to external references. In this way, the HBIM is conceived as an archive, an information collector and a unique access point to different data.

Mesh modelling was applied to decorative elements that were linked as external files to BIM elements modelled using simple shapes with comparable volume.

Parametric modelling was performed for repetitive and geometrizable elements, but some parameters were defined as instance parameters in order to edit them locally on the model to allow a better correspondence with the point cloud.

In all other cases, combined techniques were used. First of all, the direct modelling of the elements by extracting 2D profiles from the point cloud and modelling through functions such as extrusion, blending, revolution and Boolean operations.

In addition, on some sample elements (walls, vaults, semi-domes and floors), a test was performed in order to compare different modelling workflow and evaluate the better adherence to surveyed data. The test was realized in Revit environment and three different modelling strategies have been tested, in order to reach the highest level of accuracy, trying to preserve, as far as possible, the parametric feature of the objects.

Here, in particular, the test on a deformed wall is presented: non-linear development, out of plumb and deformations along the vertical development are considered.

The first tested methodology (A) (Figure 7) refers entirely to in-place modelling using only direct modelling tools. The point cloud representing the wall was sectioned with a horizontal plane at the base and at the top. The two closed profiles that define these two sections were then drawn. A blending operation allowed to create the wall starting from the base and top profiles.

The second implemented methodology (B) was to create a wall based on a surface, using the Revit function "Wall by face" that allows placing walls on non-horizontal faces of a mass instance or a generic model. Conversely from the previous case, here it is

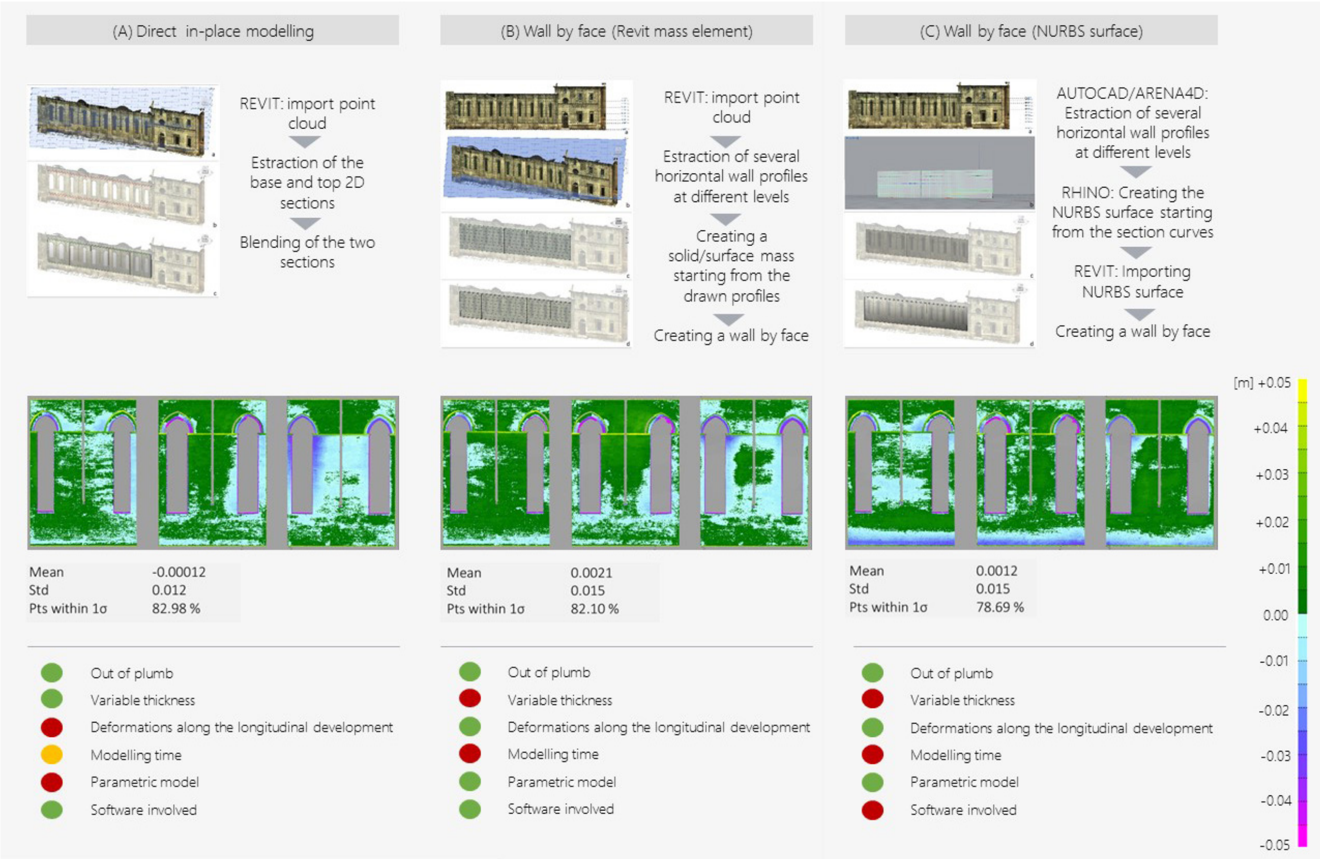

Figure 7_Summary and comparison of the three tested methodologies.

necessary to section the wall at different levels to reproduce more faithfully its conformation. Moreover, only one side of the wall (e.g. internal) is sectioned while the other will be modelled consequently. Based on the sections made, a surface or solid mass is created. On this surface, then, the parametric wall by face will be created.

The third approach (C) is similar to the second one, but it differs in the first step. As in the previous case, this workflow leads to the creation of a wall by face, but starts from a NURBS surface. Creating a NURBS surface from the point cloud, using modelling software such as Rhinoceros (Rhinoceros 2018), could ensure a higher accuracy and a better adherence to reality. Nevertheless, it requires the use of software different from Revit and could cause interoperability problems.

The comparison (Figure 7) showed that the results from a metric point of view are more or less comparable. Other factors, in particular the need to create parametric or unique elements, modelling times and efforts, must therefore be taken into account.

5.2 2D and 3D mapping

In historic buildings documentation, the surface mappings (referring at the same time to material, decay or damages) are an important requirement. They enrich the geometrical survey and give thematic information about the asset. Mappings are the basis for any restoration or conservation interventions that affect the façades of a building and are, therefore, one of the documents required by the superintendents when approving the projects. For this reason, considering a progressive use of the BIM for building conservation, it is mandatory to edit these documents directly into BIM.

Producing mappings in BIM environment is difficult. In fact, BIM software usually does not allow associating information to two-dimensional elements, such as polygons. A first response to this need is presented by (Chiabrando et al., 2017), producing 3D mapping directly on the building façade through specific adaptive components.

The methodology proposed here starts instead from orthophotos and is able to produce automatically the correspondent mapping on the 3D model.

A plug-in to Revit was implemented for:

- Associating the orthophoto to the element and displaying it in a floating window in Revit
- utilizing the orthophoto as a basic tool for 2D mapping
- Automatic 3D modelling of the correspondent elements starting from the 2D polygons.

This tool has been designed to facilitate the tasks of restorers, who usually work with two-dimensional mapping of materials, degradation or interventions to do/already done. With the tool presented here, the aim was to provide a new way of working on

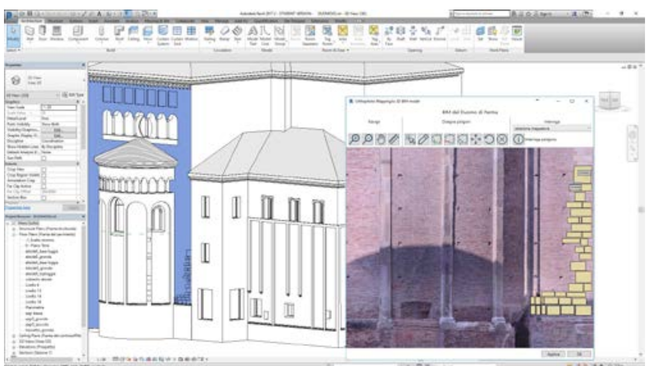

Figure 8_Example of mapping starting from orthophoto.

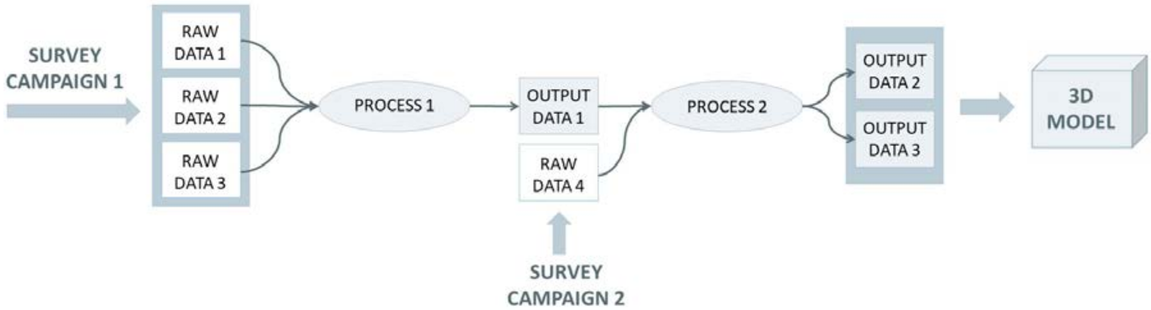

Figure 9_Schematic example of a survey process

2D drawings, directly in the BIM environment, with additional potentials that can be assimilated to GIS: the polygons drawn on the orthophoto are not simple hatched areas but vector polygons with attributes and with corresponding 3D element in the BIM model.
Moreover, each orthophoto is spatially related to the element to which it is attached.
In this way, by using the "Create Parts" function of Revit, which divides the wall surface into delimited portions, the wall is automatically divided into parts corresponding to the 2D polygons drawn on the orthophoto. This also allows the user to get mappings in the three dimensions.

6. SURVEY AND MODELLING METADATA

The final accuracy of the model is influenced by both the quality of the data surveyed and the modelling operations carried out. For this reason, since the information system is based on the 3D model, for a correct use of the data obtained from it, it is important to certify its accuracy and reliability. Metadata on survey and modelling methods, on the accuracy obtained and on the correspondence of the model to reality, are a first instrument for monitoring data quality and the basis for a rigorous and scientific analysis of the object under investigation.

6.1 Survey metadata

In complex surveying processes, documentation of the executed process becomes even more important to allow the entire chain to be reconstructed and the executed control/verification to be performed.
Therefore, a methodology to enter the quality of the survey in the database linked to the geometric model, and let the user to verify at any time the correctness of the product he is working on, has been set up.
A database section was specifically structured to host data and metadata related to the survey, which would allow its description and documentation, in order to provide the user with a tool to control and keep track of the operations carried out.
The survey has been conceived as the sum of Survey Data and Processes. The data may be either the raw data or the processes output. Processes document the type of elaborations, with the associated input and output data.
The structure of the database makes it possible to link data and processes in a sequential way, in order to reconstruct the entire sequence of raw data, processes and processed data, from the initial data produced by the instrument to the output data used for modelling (Figure 9). Both with regard to data and processes, it is possible to associate descriptive metadata and the link to specific external reference files.
The data entry is possible through specific graphical user interfaces.

6.2 Modelling metadata

As for the survey, even for modelling, it is not yet adequately defined how certify and validate BIM model quality and accuracy.
To document the modelling process these data are required:

- A description of how the modelling has been done
- Data about the adherence of the model to the surveyed data (Level of Accuracy LOA)
- Data about the knowledge (geometric, structural and material) of the object (Level of Knowledge LK)

LOA refers to the five Levels of Accuracy (LOA10, LOA20, LOA30, LOA40, LOA50) as defined by the US Institute of Building Documentation (USIBD) and described in (USIBD 2016).
For the Level of Knowledge, instead, a specific reference standard that defines this parameter does not exist. Nevertheless, this concept can be compared with the *Level of Knowledge (LK)*, provided by the Italian "Technical Standards for Construction" (Italian NTC 2009). Four different levels

Level of Knowledge	Geometry (LKG)	Structure (LKS)	Material (LKM)
LK 0 Supposed	The geometry of the structure is not known and is supposed from analogies or images.	The structure and the construction technique of the element is not known and supposed from analogies.	Materials are not known and supposed from images or from view.
LK 1 Limited	The geometry of the structure is known from 2D surveys or original drawings.	Construction details are based on a simulated design carried out according to the construction practice.	Materials are known but their properties are not available neither from constructive designs nor from test certificates.
LK 2 Appropriate	The geometry of the structure is known from 3D incomplete survey integrated with other data.	Construction details are known from an in-situ analysis or are partially available from constructive designs.	Information on the mechanical properties of the materials is available on the basis of either the original design drawings or original test certificates, or appropriate in-situ tests.
LK 3 Accurate	The geometry of the structure is known from 3D complete and certified survey, with adequate accuracy to the representation scale.	Construction details are known from an accurate in-situ analysis or are available from original constructive designs.	Information on the mechanical properties of the materials is available on the basis of the original design drawings or certificates, or by in-situ accurate tests.

Figure 10_ Implemented Level Of Knowledge (LK) classification

(LK0 Supposed, LK1 limited, LK2 Appropriate, LK3 Accurate) were introduced, divided by geometry, materials and structures, as described in the figure (Figure 10)
A section of the database was then structured to describe the modelling process (modelling technique, author, date, etc.) and to insert values related to the model's adherence to the surveyed data: LOA and LK.
This information can be entered through a specific interface and is associated to each single object modelled, since the global quality of the model could be, and is in the most cases, different from the local quality of the single items.

7. THE HBIM IMPLEMENTED SYSTEM

A BIM process applied to Cultural Heritage must respect the peculiarities of historical assets, both in terms of its geometric description and association of information. This involves considerable problems and difficulties that are still open research topics (Donato et al., 2017; Fassi et al., 2015). As far as the management of the semantic data and the model enrichment are concerned, at the time being, there are no commercial tools capable of fulfilling all the specific functions required by Cultural Heritage documentation.
The thesis implements a HBIM system with the aim to be a concrete solution to the lack of suitable instruments for Cultural Heritage maintenance, conservation and restoration. The application is an information system at the architectural scale and has been designed in order to be as flexible and customizable as CH specific needs require. It is based on a BIM 3D model of the building and, thanks to the interaction with an external database specifically structured, allows users to properly archive and query the data required to describe the building. The application is standalone and has been structured to be integrated with major BIM software and with web applications as well.

7.1 Database design phase

In order to cope with the limitations imposed by the main BIM software, which generally do not allow to create hierarchical information or to manage many-to-many relationships, it was decided to implement an external and independent database and to interface it with the BIM software (in this case Revit). In addition, this choice has allowed not to be bound to a specific software house and to create a flexible solution, adaptable to the needs of the case study and accessible through different desktop and web applications.
Database design was based on the analysis of the asset and on regulations relating to planned maintenance. The building was then classified into four semantic levels: Building, Functional Areas, Technological Elements and Technological Sub-Elements. The functional areas breakdown reflects the spatial organization of religious buildings (central nave, aisles, transept, choir etc.); the technological elements follow the guidelines for the drafting of plans for planned conservation (Della Torre, 2003) and are divided into vertical structures, horizontal structures, roofing etc.; the technological sub-elements were introduced to allow for a further breakdown of the main elements, in order to better detail the structure of the building.
At the building level, according to the DPCM 9 February 2011 and the Code of Cultural Heritage and Landscape, the building is identified uniquely through three fundamental parameters: denomination, toponymastics and cadastral data.
Since the primary goal of the implemented HBIM was to archive and manage all data about the building, document the interventions occurred and assist maintenance and conservation planning, the database implementation focused on information and data required for scheduled conservation. Therefore, the requirement-performance analysis and the methodology proposed by (Della Torre, 2003) have been adopted.
According to this approach, the quality of the built objects is expressed according to "performance" and/or conservative "problems", which, summarizing both the "requirement" for use and the "risk" for conservation, was more suitable for describing historical elements behaviour (Della Torre, 2003):
Therefore, to each technological element, data about:

- *Problems* that can affect the element
- the evaluation of *Damages* that affect the object
- the program of preventive *Actions*
- the consequent *Inspections*.

has been associated.
All this information contributes to the drafting of the technical manual and maintenance program of the conservation plan.
In addition to these data, to describe the actual state of the Parma Cathedral, the Fabbriceria administration required data entry to document the degradation of external façades (resulting in decay and material mapping) and structural monitoring. In

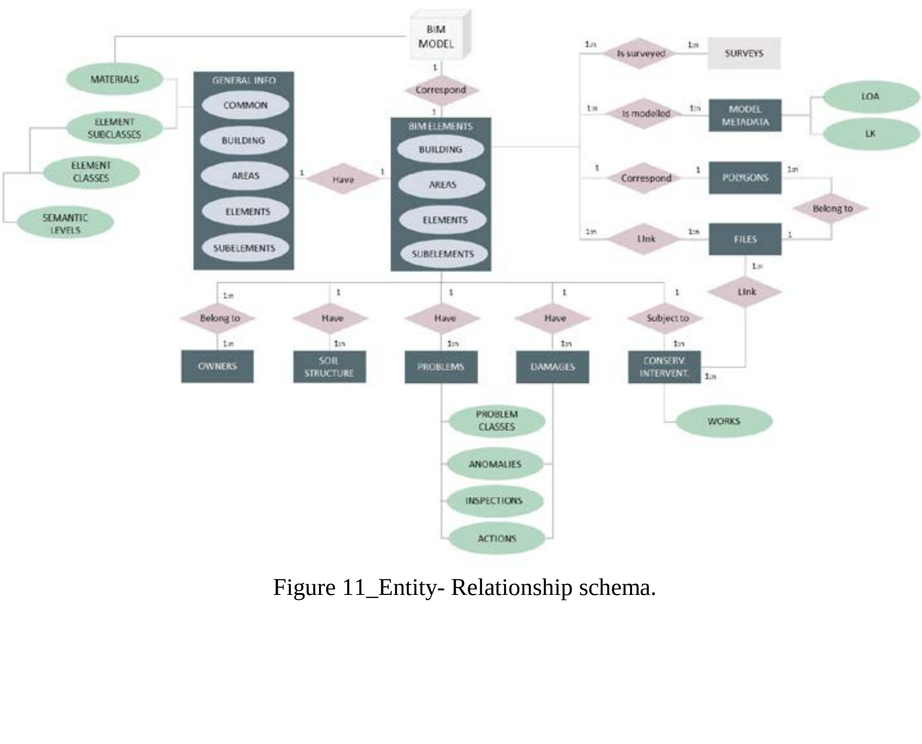

Figure 11_Entity- Relationship schema.

addition, the main documents concern: data about previous surveys, both textual and graphic data; archival data; photographic images (current and historical); historical analyses and publications about the Cathedral.
As shown in the entity-relationship schema (Figure 11), a unique atomic database entity was identified corresponding to a general BIM Element. This entity is the link between the database data and the three-dimensional model.
Despite the presence of four different semantic levels, it was decided to create a single database table as, conceptually, the four levels are the same. In fact, they all correspond to a graphic element and are BIM elements, even if with different levels of hierarchical grouping.
From the data association point of view, the structure has been designed in order to be as flexible as possible and implementable over time with different data. It was decided to organize the data into independent database tables. These tables can be associated to the element according to the needs. In this way, the user decides which data to associate with the element, making the system flexible. Additionally, it is always possible to add a new entity and associate it with the elements.
As far as the choice of the RDBMS is concerned, Microsoft SQL Server (Microsoft SQL, 2017) was used, since it can be perfectly integrated with the application structure based on Entity Framework technology, as will be explained below.

7.2 Technical features of the implemented application

The application implemented in the thesis has been developed to ensure easy usability and multi-platform implementation. The idea was to apply the same data model to different application usages (desktop and web interfaces), without changing the basic logical structure and preserving the same functions and rules.
It was possible thanks to the use of .NET Framework. .NET Framework provides a consistent object-oriented programming environment, minimizes software deployment and versioning conflicts (.NET Framework, 2017). In the present case study, the application has to be integrated with BIM software and, in particular, Autodesk Revit has been used to test this integration. Revit provides .NET compliant API, thus, for the development of application, it was chosen to operate within the. NET Framework, using the available libraries for interfaces creation, database implementation, integration with other software and on-line extension, ensuring consistency and interoperability.

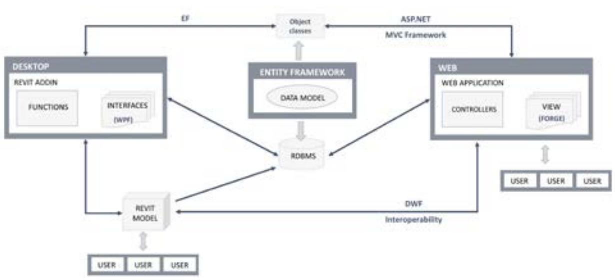

Figure 12_Architecture of the implemented application.

In particular, the Entity Framework (EF) technology was used to support the development of the whole application enabling the easy interaction with the underlying relational database. EF technology allows the developer to define in an abstract way the data model that governs the entire application. This model is compliant to the entity-relationship schema described previously. From this data model, EF automatically creates, on the one hand, the relational structure of the database, and, on the other, the object classes useful for programming the application. Therefore, all information can be managed in a consistent and coordinated way, simultaneously at the database, desktop and web application levels. (Figure 12)
For desktop side development, to make the system use easier and more intuitive, graphical interfaces and data forms have been developed to help with the consultation and implementation of the database. Windows Presentation Foundation (WPF) was used to develop graphical interfaces and to build the desktop client application.
In parallel with the development of the desktop application, its web extension has also been implemented. ASP.NET technology was used in order to exploit the same data model and on the basis of this develop the graphical interface and controllers.

7.3 Integration with Autodesk Revit

The application dialogues with Revit as a plug-in and enrich its functionalities with additional features. The implemented features can be summarized as follows: Connect/create the database; Display data about an item through the graphical interfaces; Query the database and thematic mapping the 3d model; Associate orthophoto to elements, perform 2d mapping and 3D automatic modelling from 2D elements (paragraph 5.2) and Enter survey and model metadata (paragraph 6).
Each Revit project is associated to one database, which can be accessed every time the project is opened. The user can create/connect to the specific database associated to the Revit project, by clicking the “Connect / Create DB” button in the ribbon bar. This function allows Revit to connect to the database, if it already exists, or to create a new one if it does not exist.
The second implemented function (“Info” button) allows the user to get/set all the information about the elements of the model and access directly the database. In order to simplify the interaction with the database, graphical interfaces have been implemented that make operation as data entry, data retrieve, modify and delete, user-friendly and immediately comprehensible to the user.
The user is requested to select an item. The system gets the Id of the selected item and, if it has been already stored in the database, its information is displayed; on the contrary, a new element is created. In this way, the tool allows the user not only to look at and edit the data in the database but also to enter new entities. A dialog box with information opens when the user selects the item as shown in Figure 13.
The User Interface is quite simple and gives access to all the database information. As described above, the information is classified by semantic level of element and grouped by type in descriptive forms. Each form gives access to a specific part of database data. Through these GUI, the user can enter, edit or simply retrieve all data. The available forms allow to:

- Access to all the general and morphological data about the element,
- View the problems that the element presents and the related anomalies,
- See the current and past damages in order to plan the restoration and maintenance operations,
- Access the information about restoration/maintenance/ survey works, including photos, textual and technical documents,
- View the original survey data and metadata about methodology, accuracy and execution techniques of the survey
- View or enter metadata about the model execution process

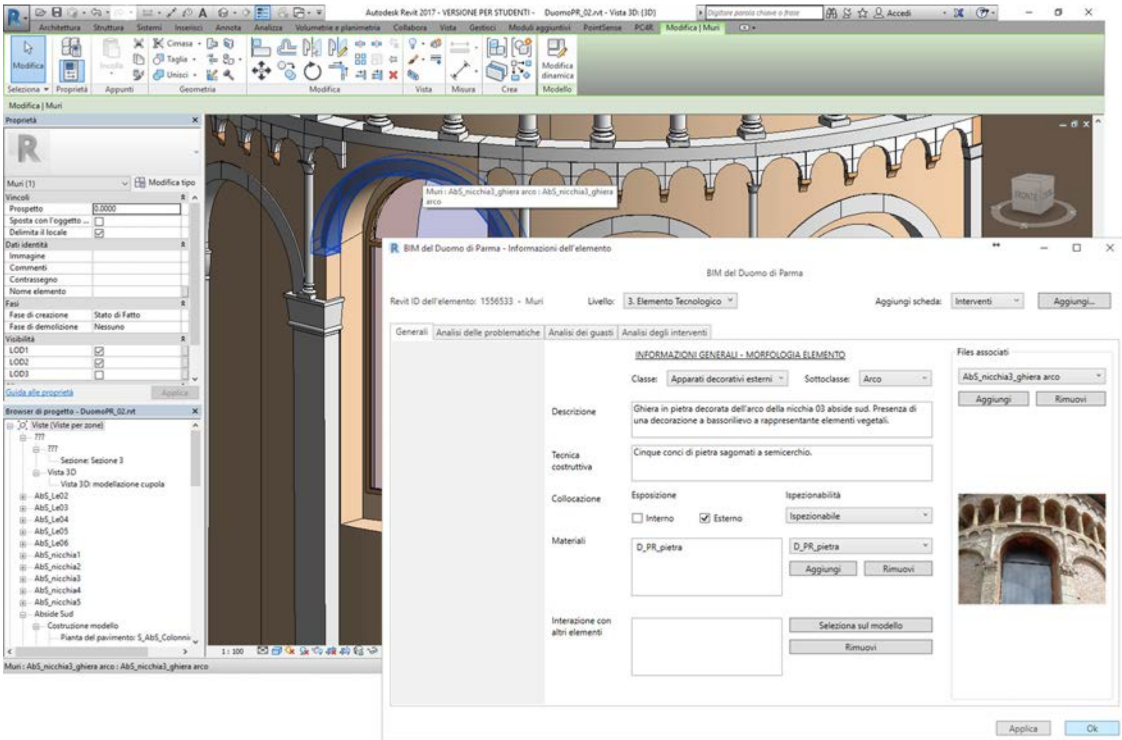

Figure 13_ Example of access to the data contained in the database directly in the Revit environment through a dedicated interface.

- link external files to the model, such as photos, orthophotos, text files, pdf, dwg etc.

In this way, all the information is connected in a consistent and coordinated way and is consultable through a single point of access.

In addition to the data entry function, in a database the query function is very important too. Directly querying a relational database implies the writing of queries (usually through SQL syntax) with different degrees of complexity, depending on analysis to perform, which does not fit the usability required by non-Information Technology specialists.

Thus, to match the user's needs, a graphical interface was implemented that allows querying the database both through text queries and a query builder, theming the Revit 3D model according to the attributes stored in the database and exporting the search results in Excel.

7.4 Data sharing and web application development

In order to allow a wider sharing of the developed application, its use via web has also been implemented. The web allows not to be bound to a specific software solution, guarantees an easy access to data even for non-experts and allows data portability even on site.

The web page (Figure 14) follows the schema developed for the desktop side. The upper part in occupied by tabs that give access to information organized in sheets.

The central part of the interface in constituted by the 3D model viewer. It is provided by Autodesk 3d Forge viewer (Autodesk Forge, 2017), which allows uploading and viewing the Revit model and its parameters directly via the web. By clicking on elements in the model the user can access to the same of the desktop side, operating directly on the database.

In this way, being the database shared between al the applications (desktop and web/mobile), all data are consistent and it is possible to access the information about the model everywhere and from any device.

8. CONCLUSIONS

In this work, the implementation of a BIM system aimed at maintenance, conservation and restoration of Cultural Heritage was presented. Its main goal was to give a concrete answer to the lack of specific tools required by Cultural Heritage documentation: organized and coordinated storage and management of historical data, easy analysis and query, time management, 3D modelling of irregular shapes, flexibility, user-friendliness, etc.

To address all these topics, the experience typical of geomatics in design and implementation of relational databases integrated into GIS software has been essential. In the HBIM the approach is comparable and only the scale of investigation changes, from the territorial to the architectural one.

The proposed solution, thanks to a freestanding database, allows, on the one hand, customizing data organization according to the asset specific needs; on the other hand, it gives more flexibility without being tied to a specific commercial solution.

The application was implemented with the specific aim of providing tools also for non- AEC experts: it gives user-friendly graphical interfaces to access the data and makes available tools for data entry, element modelling, attribute query and thematic mapping.

In addition, in any BIM process applied to existing building, the validation of the model is fundamental: geometric and semantic data have to be reliable and accurate enough to fulfil specific requirements and their reliability and accuracy should be properly documented by BIM authors. The model accuracy is affected by both the survey accuracy and the modelling accuracy, so survey and modelling phases should be certified. The thesis offered a contribution on this topic, by proposing prototype tools that allow inserting survey metadata. The system allows each modelled element to be associated to the survey products used for its modelling and also to trace backwards all the survey chain processes (up to the raw data), in order to

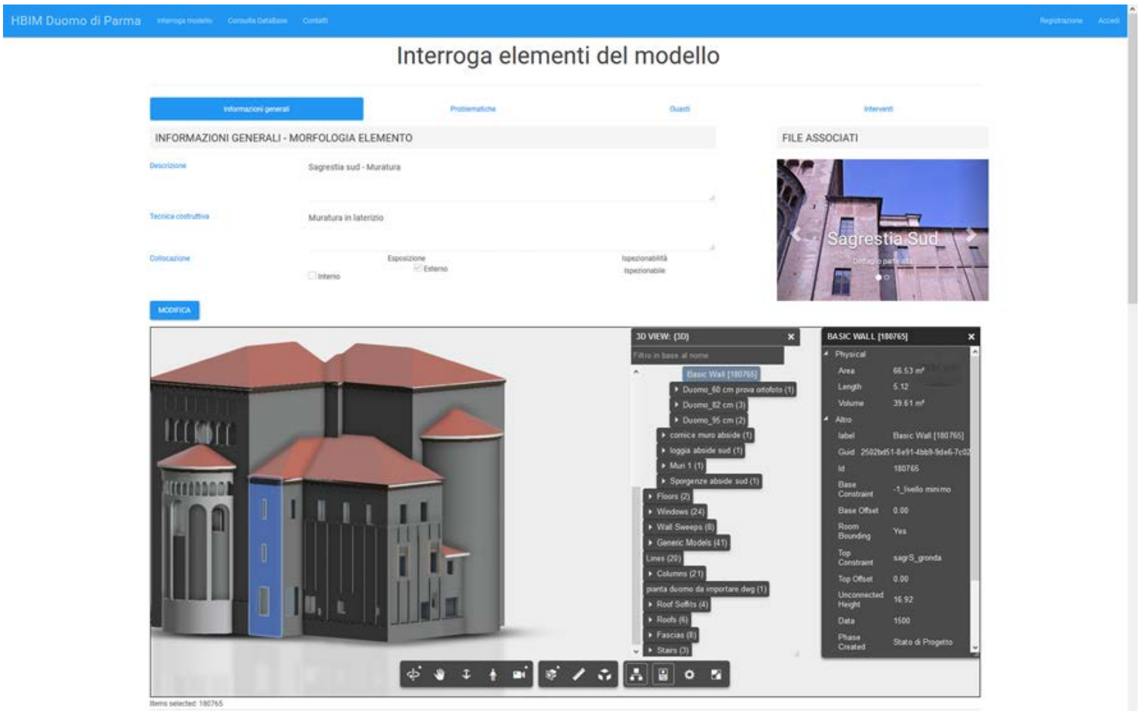

Figure 14_ Web page created for access to database data and to the 3D model.

evaluate the correctness and quality of the operations carried out.
The experimentation carried out in this research shows that the use of HBIM in the cultural heritage field is a good solution and a potential for more coordinated and efficient management and preservation. Nevertheless, a widespread application of HBIM system to cultural heritage buildings requires a large investment in terms of costs, training and processing times.
In particular, it is necessary to invest in technological development and scientific research to provide accurate and verifiable data, optimise and speed up surveying and modelling processes, overcome interoperability problems and create user-friendly systems.
On the other hand, it is necessary to have a common and shared normative references and standards for addressing processes and methodologies, in order to support the transition to BIM.
It is essential to invest in training, both to make people aware about the importance and opportunities that these tools can provide and to make BIM use effective.
Only in this way, it will be possible to create the effective and interdisciplinary dialogue between all the actors involved, which is fundamental when approaching a complex heritage such as the Cultural Heritage one.

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