PLANNED MAINTENANCE FOR ARCHITECTURAL HERITAGE. EXPERIENCES IN PROGRESS FROM 3D SURVEY TO INTERVENTION PROGRAMMES THROUGH HBIM

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Highlights

The contribution presents the first results of ongoing research begun in 2015, which fed back into a European funded project for planned maintenance of architectural heritage. The project involves Italian and Swiss partners and has as its case study the "Sacri Monti" complex, a UNESCO site inscribed in the World Heritage List in 2003. The research activity aims to create a system of maintenance procedures and protocols to be organised and made available through an easily updatable and manageable database, structured by HBIM models.

Abstract

The continuous evolution of 3D surveying and modelling techniques, using increasingly high-performance tools and applications, highlights the added value of these methods in the field of urban and architectural survey. In the case study presented, attention is focused particularly on applications useful for the planned maintenance of cultural heritage (CH). These tools and methods have a significant impact on the phases of interpretation and "physical" knowledge. They can also bring a critical contribution to the completion of models that are not only geometric but also semantic and informative, supporting 360-degree planning of the maintenance of our historical architectural heritage.
This support for scheduled maintenance has been identified in the HBIM methodology, based on an integrated 3D metric survey.
A three-year research project on this topic (Interreg Italy-Switzerland "MAIN.10.ANCE", 2019-2022), partnered by Politecnico di Torino, is currently in the central phase. The main focus of the project is a UNESCO heritage site: the "Sacri Monti" (Sacred Mountains) of Italy and those in Canton of Ticino (Switzerland), with the need for a common and shared conservation plan.

Keywords

Cultural heritage, Integrated metric survey, HBIM, Planned maintenance, Multiscale database.

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1. INTRODUCTION

The management of ordinary maintenance operations on assets of significant architectural, artistic and cultural interest is often extremely difficult and sometimes requires extraordinary efforts, in clear contradiction with the *ordinary* nature of the maintenance itself. There could be manifold reasons, but only two of them are purposely highlighted in this contribution. The first is the chronic shortage of sufficient economic resources as well as human and technically adequate figures, which the management bodies have to cope with daily. The second can be traced back to a cultural problem: the owners of a historical architectural site (i.e. municipality, local authority, parish) are unlikely to find a territorial governing body (at any level), a Protection Authority or a Foundation (both public or private), that will pay out grants to cover the cost of ordinary maintenance. Restoration works, in fact, draw more attention from the public.

Ordinary (and sometimes extraordinary) maintenance must be encouraged with appropriate scheduled actions, systematic protocols and co-funding channels, while restoration should be an exceptional event. Way back in 1994, Giuseppe Rocchi wrote: "[…] the ethical principle of restoration is to self-extinguish […]" [1].

The importance of planned maintenance *ope legis*, induced through the "Maintenance Plans" and "Maintenance Programmes" envisaged by the Public Procurement Code (Legislative Decree no. 50 of 18 April 2016, updated with Laws 55/2019 and 59/2019) is negligible compared to the real problem. It is well known that many of the entities mentioned above lack sufficient funds to implement them.

As a consequence, most of the initiatives are attributable to the awareness and preparation of the people working for these entities, who have the difficult task of coordinating and planning technical actions with different political intentions and scarce availability of human and financial resources.

This contribution outlines a work in progress within an international research programme (Transfrontier Cooperation Programme Interreg ITA-CH 2014–2020), in which the Politecnico di Torino team, coordinated by M. Zerbinatti, plays a crucial role in contributing to the evolution of an existing maintenance programme (implemented on an "experimental" basis at the Sacro Monte of Varallo Sesia) into a *model* that can be exported to different territorial areas for similar structures or complexes, but also single assets within the widespread heritage in the territory. The research project aims to create a system of maintenance procedures and protocols that have already been successfully tested with informative models and intervention management programmes, taking into account the complexity of the context and the multiplicity of information.

The goal is ambitious as it will try to combine different and sometimes conflicting instances and a large amount of information (i.e. details gleaned from LiDAR surveys useful for 3D modelling, system or sub-system that identifies the poly-material nature of the constructions investigated, construction techniques, historical, archive and iconographic sources and previous maintenance activities, with their diachronic frequency). All this takes place in a framework where the need to address the management of even the semantic aspects adequately is crucial for the development of an effective and dynamic tool.

1.1. THE OPERATING CONTEXT

Before introducing the technical and analytical part of the work, it is helpful to provide information on the overall system of the Sacri Monti and, in particular, the Sacro Monte of Varallo Sesia (Fig. 1), as well as the chapels considered in this study.

The Sacri Monti of Piedmont and Lombardy are architectural complexes of outstanding value, located in landscapes and man-made environmental contexts of considerable beauty and they were declared UNESCO site in 2003.

The Sacred Mount of Varallo was the prototype for all the Piedmontese complexes (six more were built) and for those in Lombardy, which experienced their most prolific development in the middle of the Catholic Reformation period after the Council of Trent, ended in 1563. The Sacri Monti were conceived and organised to educate the people living in the sub-Alpine area and bring them back to the Catholic faith, given the progress of the Protestant Reform. The first site where a Sacro Monte was built is the part of the mountain overlooking the town of Varallo Sesia (in the province of Vercelli). The construction of the first devotional chapels began at the end of the fifteenth century. The initial aim was to create an extremely rigorous reproduction of the holy places of Palestine. This would make it easier for people to visit or make a pilgrimage, rather than travel to Jerusalem. The first chapels, built

Fig. 1. *Sacro Monte of Varallo Sesia.*

from 1486, were very simple, combining "rural" buildings with natural caves (or rocky outcrops), reproducing characteristic models of the architectural culture of the Sesia Valley. This *modus operandi* can also be associated with the complex of chapels 2, 3 and 4, known as the *Nazareth chapels* (Fig. 2.a), examined by the work team also during their constructive evolution [2].

Similarly, the complex of chapels 5, 6, 7, 8 and 9, known as the *Bethlehem chapels* (Fig. 2.b) was built against a rocky outcrop in the hill, and then developed over time with alterations, adaptations and additions. These were aimed both at directing the water that filtered through the rocks away and adapting the buildings to the changing needs of scenographic representation and use. For example, the public no longer crossed the "scene" from the inside but observed it from the outside through stained-glass windows and wooden gratings.

Lastly, this study also focuses on chapels 24 (Fig. 3.a), 28 (Fig. 3.b) and *Palazzo di Pilato* (Fig. 3.c) (with nine chapels inside) all of which overlook *Piazza dei Tri-*

Fig. 2. *(a) Complex of Nazareth with chapels 2, 3 and 4 (left). (b) Complex of the Nativity with chapels 5, 6, 7, 8 and 9 (right).*

Fig. 3. *Chapel 24 (a). Chapel 28 with loggia in the upper part (b). North Façade (c1) and South Façade (c2) of Palazzo di Pilato.*

bunali (Court Square), one of the two urban areas of the complex.

We have inherited and are duty-bound to manage this important heritage, carrying out accurate planned maintenance. For several years now, the Body that manages the Sacri Monti has been preparing control programmes and maintenance actions, based, for example, on the seasonal cycle, the best timing identified for the artefacts, and on sporadic exceptional events.

1.2. HBIM METHOD IN SUPPORT OF THE MANAGEMENT OF CULTURAL HERITAGE

The management and safeguarding of complex systems, like our architectural heritage, require the adoption of strategies aimed at:

- the integration of data from various sources (historical and archive documents, timing schedules, maintenance plans, specialist reports, etc.);
- the digital display of this information and the simplification of its use.

As regards the metric documentation on an architectural scale, the guidelines available tend to use documentation methods which are now quite widespread and in regular demand, and which involve the integration of several sensors and instruments (Light Detection and Ranging - LiDAR, Autonomous Aerial Vehicles - AAVs, Mobile Mapping Systems - MMS) [3, 4]. As far as digital representation is concerned, the BIM (Building Information Modelling) methodology, intended as a detailed representation of construction generated using *smart components*, can be a good solution, on condition that it is applied to existing historical buildings in a metrically correct way.

The adoption of this method, applied to cultural heritage, has become increasingly common in recent years [5–7] with the name of HBIM (Historical BIM) [8, 9]. There are still numerous limitations to the use of these models, such as difficulties in the parameterisation and modelling of complex geometries not envisaged in object-oriented software (designed for the representation of buildings from scratch, characterised by standard and regular elements). Nevertheless, easy data management [10], and the consequent simplification of the updating phases is the main reason why this methodology is becoming so popular. The purposes for which it is preferred to traditional methods are numerous. These range from the representation and computation of forms of alteration and degradation [11, 12] to structural and seismic vulnerability studies [13], through to the input and management of a considerable amount of multi-source data [14–16], which can also be managed on urban-territorial scale platforms [17]. The HBIM method was explicitly chosen in view of this potential, with the support of point clouds for the modelling phases.

2. METHODOLOGY

The particular arrangement of the 45 chapels of the Sacro Monte of Varallo Sesia, set on a rocky spur at an altitude of about 600 m a.s.l., made it necessary to use a "multisensor" approach [18, 19], with both image-based and range-based techniques, for the survey of the complex.

The GPS/GNSS (Global Positioning System/Global Navigation Satellite System) and the total station have allowed the definition of the high-precision geodetic network, with topographic measurements. AAVs (drones) were used for the acquisition of aerial photogrammetric data of areas which would have otherwise been difficult to reach and Time of Flight Terrestrial Laser Scanner (TLS) systems were used for the accessible parts of the site and the chapel interiors. SLAM (Simultaneous Localisation and Mapping) technologies were tested too, despite not yet being consolidated in the field of geomatics. Tests were also carried out using low-cost and COTS (Commercial Off The Shelf) sensors, which allow the reduction of acquisition time and speed up survey operations [20, 21]. These surveys and the following data processing steps resulted in the determination of the point clouds of the chapels. These point clouds can be imported into an *object-oriented* software and used as the basis for subsequent 3D geometric modelling phases. The HBIM products were subsequently enriched with different types of information, such as technical-construction aspects (materials, forms of alteration and degradation) or historical and documentary data, etc. For the lexicon of the forms of alteration and degradation, reference has been made to UNI 11182:2006 *Cultural Heritage - Natural and artificial stone materials - Description of the form of alteration – Terms and definitions*. This information was then exported to allow the structuring of an external relational database in MS Access, available for the management of the Sacri Monti system.

2.1. INTEGRATED METRIC SURVEY

The data acquisition activity was carried out in several surveying campaigns which began in 2015 and are still in progress. As previously mentioned, some of the points of the planimetric grid were measured using the GPS/GNSS technique in static mode and other high-precision points were measured using the traditional topographic technique. Laser scans were performed both indoors (attic, porticoed areas, loggias and chapels) and outdoors, (Fig. 4) to obtain dense metric data with a resolution of 1 point every 5 mm.

However, as certain areas are not fully accessible due to the conformation of the terrain and the prominent position of the spur on which the complex is situated, it was necessary to use AAVs to survey not only the roofs but also those parts of the building that would be otherwise impossible to reach. For this purpose, several nadiral (90°) (Fig. 5) and oblique (45°) flights were planned for a take-off area >38,000 m^2 and a height between 499 and 642 m a.s.l. The drones used were: in the case of the two squares, a hexacopter developed by the DIATI of Politecnico di Torino with a 24.7 Mpixel SONY camera and frame size of 4,000x6,000 pixels and, in the case of the Nazareth complex, the Phantom 4 Pro commercial drone by DJI, equipped with a 20 Mpixel 3-axis stabilised camera and a 1-inch sensor.

2.2. DATA PROCESSING: POINT CLOUDS

Following the acquisition phases, photogrammetric data and laser scans were processed, ensuring that the resi-

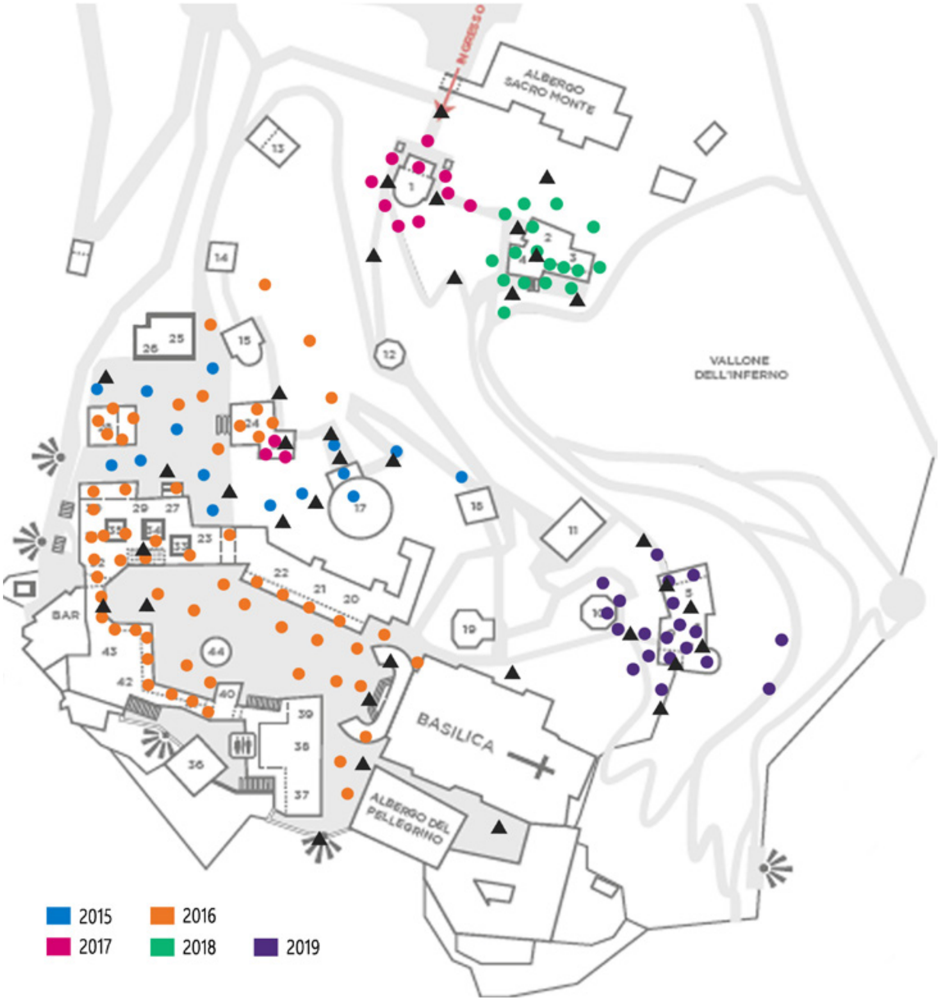

Fig. 4. *Vertices of the framing network (triangles) and laser scans performed.*

dues on the markers were less than 10 mm. This limit was set on the basis of the final representation scale desired of 1:100.

As regards photogrammetric data, different types of software were tested, and the resulting point clouds were compared (C2C - Cloud to Cloud, and density) to determine which solution was the best considering: the advantages and disadvantages of each software. More specifically, Context Capture by Bentley System, Agisoft Photoscan (now Metashape), Visual SFM, Pix4D and MicMac were

Fig. 5. *Example of AAV flight plan over the whole complex and the result of the alignment of the photos acquired.*

used. After processing, comparing, cleaning and filtering the point clouds, the data fusion process was carried out, allowing the integration of the laser point clouds with the missing parts (covers or inaccessible areas) resulting from the photogrammetric ones (Fig. 6).

In addition to the processing of point clouds, the DTM (Digital Terrain Model), a model of the earth's surface that excludes all anthropic or vegetational elements, has also been developed. Within the 3D object-oriented modelling environment, this element provides a topographic surface on which to place the buildings, based on the real slopes and contours of the ground. To achieve this, we used Envi LiDAR software, which exploits the previously generated photogrammetric point cloud. In the case of the Nazareth complex, for comparative purposes, the DTM was defined directly inside the Autodesk Revit software. Although the result of the second solution is acceptable, it is not as reliable as the previous one, leaving room for possible simplifications.

Lastly, after generating the DTM, the point clouds of the individual chapels were broken down into architectural components, for easier management in *Autodesk Revit*. They were then exported via *ReCap 360* (Reality capture) in *.rcp* format, recognisable and supported by the object-oriented software.

3. RESULTS

3.1. HBIM MODELLING

What distinguishes parametric modelling and the BIM method from the common 3D modelling of architectural heritage is the possibility to integrate not only parameters and data such as geometry (coordinates and surfaces), topology (the connection between elements) and photometry (visual characteristics of surfaces) but also parameters on a varied set of aspects, from technical to historical.

As object-oriented software is not yet able to fully manage complex geometries such as historical architectural elements of different shapes and volumes, it was considered more important to model architectural objects which, while simplified, still allow the creation of a database with information useful for planned maintenance. The achievement of a high level of detail and full correspondence with the actual geometries has, therefore, become less important than the semantic component of the model. From this point of view, details such as the tapering of the walls, the entasis of the columns or the different ratio between the rise and tread of the historic staircases were purposely not shown. Nevertheless, more generic parameters typical of historical architecture, such as the dimensions of the plinth, collar, echinus,

Fig. 6. *Point clouds resulting from the integrated metric survey and obtained with different software.*

shaft, bull, etc., of columns have been considered in the realisation of the specific families, on the basis of Architectural Manuals [22].

In the first phases of modelling, some *plug-ins* for the semi-automatic recognition of elements from point clouds (walls, columns, doors and windows, fixtures and orthophotos) were tested, and one of these, *FARO As-built*, was also used in the final phases for the comparison of the metric congruity between the point cloud and the HBIM model [23]. After generating the overall geometry of the building with the *system families*, *adaptive generic metric models* were used to model complex elements such as ribbed barrel vaults, cross vaults and sail vaults; for the remaining architectural elements, such as columns, balustrades, chapel grilles, entrance portals and some stone columns, *generic metric models* were used instead (Fig. 7).

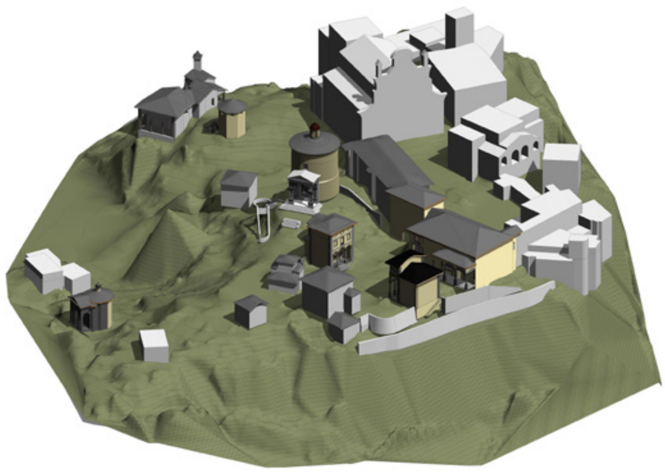

Fig. 7. *Overall view of the HBIM models already structured, with mass visualisation of those in progress.*

3.2. THE MANAGEMENT OF A DATABASE FOR PLANNED MAINTENANCE

The proposed database must be capable of providing a support tool for the management and maintenance not only of a single architectural asset but of an entire urban complex included in a bigger supra-regional territorial system. The structuring of this database, associated with the HBIM models, has first to manage a considerable amount of historical and technical data, to be organised, updated and made available in the simplest possible way to those in charge of protection. Then it has to meet the need to create a standardisable data model versatile enough to be used, albeit only partially, in the broader context of "widespread" cultural heritage and its conservation.

In the initial phases of the work, we proceeded with an entity-relation scheme (E-R), starting from the conceptual model and then translating it into a logical model (Fig. 8).

The entities represent complex concepts with an autonomous existence, which contain the instances, i.e. single objects of the class represented. The relations, on the other hand, represent the logical links between two or more entities. This database is connected to the HBIM model through the Revit *DB-Link* plug-in and is integrated with the tables generated automatically by the software and those added manually after export. In order to correlate the database extracted from Revit with the new tables, it is necessary to add *shared parameters*, which are subsequently incorporated into the project. These parameters concern the identifiers of the complex and the number of the chapels, their names, the restoration activities carried out, the materials used for the structures, etc. If several chapels correspond to a building, as in the case of *Palazzo di Pilato*, masses were generated and associated with the information of the individual chapels. The same *project parameters* were assigned to the categories corresponding to the geometric elements of the model: details, windows, mass, materials, generic models, walls, floors, stairs and roofs.

All the data inserted in the HBIM models have been exported in this way to be consulted with *MS Access* software (Fig. 9.a). Within MS Access, in addition to manually adding different types of data, consultation windows have also been created. These allow the user to enter the code of an element, view all the associated information and update it. Different consultation windows were set up for the database of the Sacri Monti: some related to single elements or activities, such as masonry or restoration activities (Fig. 9.b), and others that are more general to provide information on the system of the Sacri Monti of the Prealpine Region.

In this way, an "easy to manage" tool has been set up, with a workflow that allows the automatic update of the data in the database starting directly from the HBIM digital model. Moreover, being managed with software

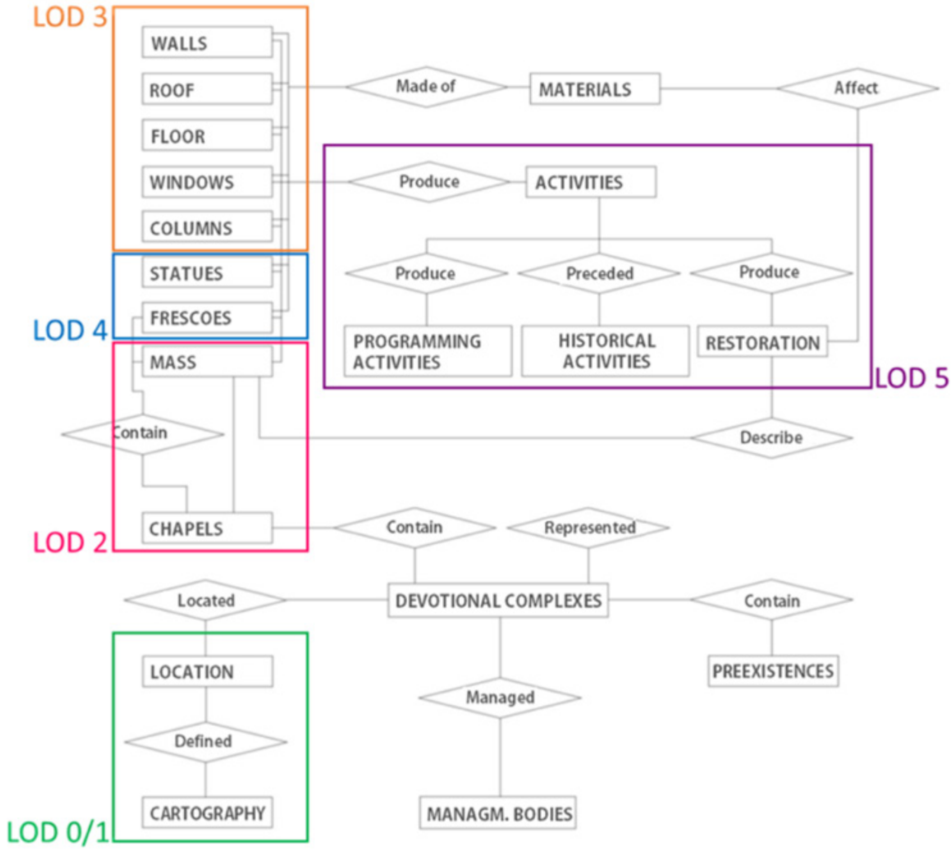

Fig. 8. *Entity-relation scheme with the planning of activities and architectural components. The highlighted squares define the different Levels of Detail (LOD) of the database to be deepened in future developments of the Main10ance project.*

that can be easily installed on any portable device, such as smartphones and tablets, it guarantees the availability of information even during inspections, on-site activities and all ordinary and extraordinary maintenance activities. Being constantly updated and connected with the geometries of the 3D model, it is also suitable for the drafting of time schedules, metric estimates and the construction of abacuses of the architectural elements.

Fig. 9. *Example of tables exported from Revit into MS Access (a) and specific query window for the restoration of Palazzo of Pilato (b).*

4. CONCLUSIONS

We can state that the use of HBIM models for the management of built heritage is certainly useful and suitable to set up operational tools to help and support conservation activities, and to draw up scheduled maintenance plans. In addition, the possibility to link and relate different models in a unique project allows to overview and also control complex historical systems like the one of Sacri Monti.

Nevertheless, despite the extensive potential of this tool (Tab. 1), there are still many critical issues. In order to define a model similar to the actual building, the HBIM modelling still involves a significant series of approximations and simplifications. Moreover, using this data, it is not possible to define many parameters that are useful for BIM, linked i.e. to elements that are not visible and detectable without further investigation (stratigraphy, bearing loads, etc.). Complex elements are mostly processed in specific 3D modelling environments (i.e. Rhinoceros) or with local models and, after being imported into the project, these geometries are not always recognised or inserted into the appropriate families. Consequently, the parameters of the family are not automatically associated with them.

Furthermore, interoperability between different types of software is not yet fully guaranteed.

To this end, the future developments of the MAIN.10.ANCE Interreg project are expected to include the update of the entity-relational scheme, structuring it in compliance with existing standards, nomenclatures and classifications, so that it becomes effectively interoperable and can be easily integrated into other databases.

The use of dictionaries such as Art and Architecture Thesaurus (ATT) published by the Getty Foundation, compliant with ISO and NISO standards for the creation of dictionaries, or the study and application of ontological models, could provide a solution in this sense, along with new research perspectives. Lastly, the particular nature of this case study, included in a broader system suitable for management at territorial level, makes the use of georeferenced HBIM models of the chapels in a GIS environment particularly interesting, allowing the management of geospatial and architectural data in different levels of detail, useful for multiscale analysis.

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STRENGTHS (PROS)	LIMITS AND CRITICAL ISSUES (CONS)
Georeferenced model	Purely representative model of the real element
Centimetric precision	Loss of millimetric precision
Mapping info: DTM	Difficulty with modelling curved details
Model with multi-source data	Absence of stratigraphic info
Quick and reliable reconstruction of geometries	Complex modelling of historical elements
Graphic info and info on materials	HBIM method not yet standardisable
Collective work	Interoperability between various types of software
Consistent and updated documentation	Complex database
Unified digital archive	
Info on degradation manageable using abacuses	
Monitoring of operations and reporting	

Tab. 1. *Main pros and cons of the use of the HBIM method.*

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