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Recently, the scientific community is working on Historic Building Information Modelling and Management (HBIMM) in order to improve the interoperability among information/data in different types and formats. This circumstance has traditionally led to difficulties and errors in knowledge, diagnosis and refurbishment. The proposal of the operative method has been tested for managing the historical buildings' knowledge system by using relational databases and time parameter creating a 4D-HBIMM simulation for diagnosis of decay and settlements toward data computing. The information, as BIM parameters, refers to historical and constructive evolution, previous interventions, crack patterns and degradation condition of an Augustinian Monastery (southern Italy), as sample of an agglomeration of buildings, interested by previous refurbishment interventions, decay and kinematic movements. The advantage is the rapid data consultation and the possibility of comparison between geometric-typological and pre-diagnostic information in order to understand the actual causes of the decay and kinematic settlements.

Keywords: Refurbishment, Historic Building Information Modelling (HBIM), Information Management System, Diagnosis, Decay mapping, 4D-HBIMM, 4D Simulation

1. Introduction

1.1. Motivation

Restauration, refurbishment and maintenance of historical buildings implies the accurate knowledge acquisition of geometrical asset, the materical-constructive characterization and the analysis of constructive evolution, including prior conservation and refurbishment interventions that generated the current conditions of cultural assets (Binda and Cardani 2015). Therefore, the archival information may be combined with on-site survey for recognizing modifications and stratifications and understanding if the combination of identified building phases and constructive elements are causes of degradation and existing kinematic settlements, without errors of interpretation (Fatiguso, De Fino, and Scioti 2017). In traditional practices, the acquired information is collected as paper-based or digital documents that are often onerous to consult and manage, above all if comparing data connected to different chronological periods (Ciribini, Ventura, and Paneroni 2015). These circumstances may cause the risk of misunderstanding of actual building conditions and pathologies' causes, consequently the implementation of incompatible actions (Bruno, De Fino, and Fatiguso 2018). The computational nature of the Historic Building Information Modelling (HBIM) approach demonstrated flexibility in managing heterogeneous datasets about geometries and properties of structural elements, multiple construction technologies (walls, vault system, roof etc.), and decorative layers (frescos, stuccos and frames) contributing to the explanation of construction sequences and adopted technologies (Brumana et al. 2013).

For this purpose, this paper concerns the introduction of the time parameter within an HBIModel as essential for a clear and immediate visualization and analysis of the morphological layout, the anachronistic constructive evolution, the stratification of the interventions, the development of cracks and degradation phenomena.

Surely, a model can represent a solid basis for the interpretation of the construction evolution (Charbonneau et al. 2018), but it could also visualize and analyse the current future building conditions.

Furthermore, the challenge of 4D modelling is an efficient integration and management of multi-data sources (specifications, requirements, etc.) (Rodríguez-Gonzálvez et al. 2017), even as real support to the diagnosis and the decision of interventions.

As a result, this research deals with the significance of the research in 4D reconstruction as the integration of 3D models and databases proposing the 4D-HBIMM, a methodology for the documentation and the analysis of historic buildings that can be innovatively implemented with existing BIM tools. This method is an additional phase of the Diagnosis Aided Historic Building Information Modelling and Management (DA-HBIMM) as it completes and manages the knowledge framework, and it is oriented toward the automation and computing in the building diagnostics (Bruno and Fatiguso 2018) with the aim of supporting decision for refurbishment and restoration and recognising the correct diagnosis of the causes on which to intervene, without further compromising the building.

The 4D-HBIMM will be a constantly evolving interface on which to progressively add future refurbishment and restoration interventions, allowing interoperability among stakeholders. It integrates the Historic Building Information Modelling (HBIM) with the Information Management and 4D simulation in order to achieve the abovementioned objectives, employing the capability of BIM tools.

The analysis of the existing research about HBIM and 4D reconstruction (Sub-section 1.2) surveys gaps and challenges in literature and practice that reveals the absence of an operative method with the aims of collecting, classifying, managing and sharing information and data relating to construction phases, transformations and interventions over time, and recording the state of previous and current decay phenomena of an existing building, benefiting from the Information Management.

The workflow of the proposed method is explained in Section 2 (Methodology) and it is divided in five steps: A) Preliminary Information Collection (Sub-section 3.1.), B) Reverse engineering (Sub-section 3.2); C) "As built-as damaged" HBIM (Sub-section 3.3); D) Information Management (Sub-section 4.1) and E) 4D-HBIMM simulation (Sub-section 4.2). The method will be validated with a pilot study case (Section 3), an Augustinian Monastery in Trani, southern Italy, a historical artefact that underwent transformations and refurbishment interventions. It still experiences conditions of degradation and kinematic motions related to the sequences of construction events, transformations and interventions. Finally, the Section 4 illustrates results, while Section 5 regards conclusions and future developments.

1.2. 4D Simulation and data management

The knowledge of historic building evolution over time is essential for assessing the current condition and defining strategies of interventions (Binda and Cardani 2015). Traditionally, the temporal analysis and reconstruction were executed through heterogeneous documentary sources (mostly paper-based sources) and the results reported in drawings and reports. The development of innovative technologies for 3D modelling and data management facilitates the 4D reconstruction. In fact, the use of integrated survey techniques (aerial and terrestrial laser scanner, photogrammetry, etc.) - as a basis for 3D reconstructions in the form of polygonal mesh or parametric objects with a high degree of accuracy (Antón et al. 2018) - can consent the visualization of the constructive evolution of the historical artefact through the introduction of the time factor for a better understanding of building conditions.

The temporal simulations have the advantage of being non-invasive methodologies for analysing and monitoring historical sites and artefacts as they let visualizing the development and transformations suffered over time by the historical heritage (Rodríguez-Gonzálvez et al. 2017), analyse the risks to which they may be subjected (earthquakes, erosion, etc.) (Fieber et al., 2017) and verify the adequacy of future recovery interventions. Additionally, the reconstruction of three-dimensional diachronic models allows virtual access to urban spaces or partially destroyed historical artefacts (Rodríguez-gonzálvez, Campo, and Muñoz-nieto 2019; Hejmanowska and Mikrut 2017) which can be implemented with Virtual Reality (Kersten et al. 2017) for an immersive use of the model generated by technicians and users (Lee et al. 2019). Therefore, specific methods and tools are needed for the integration of the knowledge about the environment with the aim of accessibility, management and global visualization.

The GIS (Geographic Information System) and BIM (Building Information Modelling) models, thanks to their link to database, could integrate data and represent the real world from different input like integrated surveys (Vacca et al. 2018). They are not mutually exclusive but rather complementary methods used to support the decision-making process and the problem solving according to the architectural heritage scale (Rodríguez-Gonzálvez et al. 2017). BIM tools are used in architectural level (walls, doors, decoration), instead GIS tools are used in urban level (terrain, land parcels and outdoor data), traditionally paired with two dimensional data (Templin et al., 2019). In addition to the possibility of modelling elements with a high level of detail (frames, capitals, handles, etc.), BIM modelling is characterized by an inherent hierarchization of architectural elements that facilitates the control and navigation operations of 3D models.

1.3. HBIM Background

The HBIM approach developed starting from the potentiality and the tools offered by the BIM as knowledge database and combining digitalization and Computer Vision (Murphy, McGovern, and Pavia 2009; Volk, Stengel, and Schultmann 2014; Barazzetti et al. 2015;

Murphy et al. 2017). The first efforts attempted to define the digital modelling and management approach of the historical building with BIM, investigating the automatic modelling procedures from integrated survey (Arayici 2007; Murphy, McGovern, and Pavia 2009). Nowadays, many academic researchers are still engaged in refining and deepening the potentiality of HBIM in the following challenges (Bruno et al. 2018):

1. The “Scan-to-BIM/Point-to-BIM” process from the data capture and reverse engineering aiming at automatic recognition and conversion of 3D surfaces into parametric models for complex geometries and morphologies, in order to avoid simplifications and inaccuracies. Nowadays, manual or semi-automatic procedures are widely employed for modelling historic buildings with some drawbacks (Tang et al. 2010; Pətrəucean et al. 2015; Luigi Barazzetti 2016; Volk, Stengel, and Schultmann 2014).
2. The semantic enrichment of the HBIM models with the aim of generating an "as-built/as-damaged" HBIM model which collates tangible information (materials and construction techniques, transformations over time and their motivation) and intangible information (historical images and texts, narration and music, historical value and meaning) (Bruno, De Fino, and Fatiguso 2018; Fai et al. 2011).
3. Investigative objectives involve identifying methods of visualization and analysis of the degradation status, traditionally linked to the completion of the in-situ survey reports and their transcription in CAD drawings, now evolving as population of the HBIM models with different methods (Quattrini et al. 2015; Rodríguez-Moreno et al. 2016; Bruno et al. 2017; Brumana et al. 2017; Chiabrando, Lo Turco, and Rinaudo 2017) that could be able to identify the actual causes of deterioration and structural instability introducing related information and metadata in the HBIMM (Bruno and Fatiguso 2018).

4. Additional requirements as the semantic information organization and management (Megahed 2015) have been identified within the knowledge phase for supporting the refurbishment project (Quattrini et al. 2017). This aspect could be resolved with the innovative ICT technologies based on Integrated Project Database (IPDB) (Mocerino 2017) and the cloud-based applications for sharing project information (Afsarivet al. 2017), as experimented with new constructions. The representation and management of information and knowledge during investigation activities may have support by an ontology-based model in order to provide flexible and reusable methodologies of structured and accurate knowledge, integrating each investigation process about the preliminary knowledge acquisition, the assessment of the historic value, diagnostics, project, execution and maintenance (Acierno et al. 2016; Cacciotti, Blaško, and Valach 2015). In more recent works, the computational BIM is an additional research direction being undertaken toward innovation (Succar 2009; Porwal and Hewage 2013; Arayici et al. 2016) for elaborating information and data through a set of logical and analytical rules. This step forward enhances the definition of a coherent knowledge base for decision support (Bloch and Sacks 2018).

1.4 Outcomes of literature review

As a result of reviewing literature and practice, the research question is about the possibility to employ the HBIMM methodology for managing knowledge about constructive evolution and building conditions in order to diagnose the real causes of decay and settlements in historic buildings. The main aim is overcoming the gaps of traditional processes that are based on the collection and comparison of paper documents whose results are resumed into several digital files, difficult to read. The challenge is the creation of an operative method that connect 3D models and temporal digital data and information within a unique and interoperable platform aiming at the semi-automatic diagnosis and identification of interventions. In contrast to what indicated by Charbonneau et al. (2018) (Charbonneau et al. 2018) who specified that the BIM platforms are not appropriated tools for 4D modelling of architctural heritage, this research experiments with the appropriateness of the HBIM approach in the 4D reconstruction.

Existing approach for documenting the transformations over time within the HBIM model has been supported by classifying each BIM element by its historical phase through the creation of a specific Project Phase employing the "Manage-Phases Box" in Revit (Rodríguez-Moreno et al. 2016). However, the above-mentioned approach is limited to the manual selection and visualization of a hystorical phase per time and it also does not allow semi-automatic assessment of decay and settlements because of static browsing of the Property Palette per each element.

The proposed operative method, within the DA-HBIMM approach, aims to fit challenges and overcome gaps in knowledge providing a system that correlates the HBIM model with structured databases in order to manage the constructive evolution, the previous refurbishment interventions, the motivations of their execution and the description of the current state of conservation throught semi-automatic procedures. Indeed, the understanding of the causes of degradation and constructive evolution will be supported by two complementary operations. On the one hand, the management of database information, structured in property categories, using conditional query tools; and on the other one, the 4D simulation of the real temporal dynamics of the constructive evolution. Through the combination of these two operations, it will possible supporting the identification of the causes on which it is necessary to intervene with coherent works.

2. Methodology

As stated by Rodríguez-gonzálvez et al. (2017) (Rodríguez-gonzálvez et al.,2017), temporal analysis and multi-temporal 3D reconstruction is paramount for the preservation of historic buildings and support decisions about refurbishment and restoration. The implementation of fourth dimension of time provides a multi-temporal representation of 3D geometrical model as an innovative method aimed at the formulation of hypothesis of constructive evolution and, consequently, the selection of coherent interventions. In this research, the proposed methodology starts from this rationale and makes use of the potentialities of the HBIM approach for testing the role of 4D-HBIMM in the analysis of constructive evolution and decay condition, supporting the planning of interventions. The employed tools belong to the BIM methodology because it integrates 3D modelling and knowledge Database management for quickly obtaining reliable information (Sah and Cory 2008).

The Figure 1 illustrates the workflow of the proposed methodology:

1. Preliminary Information Collection (Sub-section 3.1);
2. Reverse Engineering (Sub-section 3.2);
3. “As-built/as-damaged” HBIM (Sub-section 3.3);
4. Information Management (Sub-section 4.1);
5. 4D-HBIMM simulation (Sub-section 4.2).

The first step concerns the Preliminary Information Collection (A). The preliminary knowledge consists of historical and photographic memories, archival documents and prior drawings. In particular, the understanding of the constructive evolution begins from the study of historical texts and project documents, stored in the archives. Secondly, a raw geometric survey, a preliminary analysis of materials/construction techniques and analytical and typological studies about building conditions have been carried out.

The second phase is the Reverse Engineering (B) that can be completed by updating prior CAD and paper drawings via traditional direct survey, by aerial and terrestrial laser scanning and photogrammetry, or a combination of survey techniques. The selection of the suitable methods for geometric survey depends on project budget, environmental conditions, surface properties, required detail and accuracy, object dimensions. In this research, the geometric survey has been carried out starting from the prior CAD and paper drawings integrated with photogrammetric acquisitions.

We recall that the objectives of this research case are not the 3D modelling from point clouds and the quantitative evaluation of the Accuracy Level of three-dimensional models (Antón et al. 2018) but the understanding of a methodology for the management of assets' information in order to aid the decision-making of intervention strategies on historic buildings. The photogrammetric survey interested the most representative rooms of the constructive techniques and the state of conservation: a room at the ground floor and the main stairwell with evident cracking and deformations; in addition, they presented the most suitable environmental conditions, such as light, colour variations, workers' safety and, likewise, the possibility to move within the space free from scaffolding.

The equipment for photo acquisition is a CANON D600 reflex, 18-55 mm optics, following an acquisition plan to ensure the overlap of photograms (70%) and the overall effectiveness of the acquisitions and subsequent processing. The set of photographs was used for the 3D rendering in the form of a point cloud and photorealistic reconstruction (textured mesh) via image matching and the Structure for Motion (SfM) algorithms, with the aim of capturing and sharing information about the state of degradation (damp spots and crack patterns). This operation was supported by the use of the software AgiSoft Photoscan.

The data acquisitions were elaborated for two purposes: generating the point cloud to be employed for BIM modelling and the 3D texturized mesh to be linked to the BIM model for visualizing the real conditions and decay patterns. In the first case, the point cloud is generated as sparse and dense cloud from photos, then exported as *.sat. This file format was imported into the parametric object modelling section of the employed BIM software Autodesk® Revit®. While, in the second case, the point cloud was automatically polygonalized, setting a medium quality decimation and thus obtaining the polygonal mesh of the building. By using the parametric operator of polygonal decimation, it was possible to preserve the mesh's UV mapping, while leaving the possibility of experiencing progressive reduction coefficients, hence allowing the evaluation, in a perceptive way, of the correct representation of the shapes that constitute the two rooms. Because of some obstacles during the survey process (i.e. floor covering accumulations of rubble), it was necessary to use manual instruments of polygonal creation, so as to interpolate the single vertexes of the perimeters of those areas difficult to reach. Furthermore, it was verified the correct orientation of the normal polygons of each element. The resulting mesh was exported as *.obj and inserted in a web viewer, Sketchfab®.

Thirdly, the "as-built/as-damaged" HBIM (C) can be created using the prior CAD drawings for Boolean operations and parametric object placement, or the "Point-to-BIM/Scan-to-BIM" process. This last process may be performed as i) the automatic conversion of point cloud/meshes - captured via laser scanning or photogrammetry - into BIM objects with plug-ins capable of processing geometry recognition algorithms (Jung et al. 2014; Wang, Cho, and Kim 2015; Paiva et al. 2018) or converting meshes into NURBS or ii) the import of point clouds into parametric modelling tools, in order to be used as a metric reference for manual procedures (López et al. 2018). The HBIM model must be modelled with the Level of Development (LOD) 500 (G202-2013 Project BIM Protocol) corresponding to the Italian LOD F (UNI/CT033-GL05 2017).

The specific provisions of the Italian UNI 11337-3-2017 introduces the LOD G for updating the model after refurbishment/restoration/maintenance during the building life cycle management (Brumana et al. 2017).

In the current case study, the "as-built/as-damaged" HBIM has been mostly modelled from the updated 2D drawings. The architectural components were manually modelled through two different methods: parametric library objects (openings and related decorations, slabs, foundation micropiles, barrel vaults, etc.) or solids, as stairs and vaults because they are based on trapezoidal plans.

Whereas, some geometric primitives of vaults, openings and cracks have been traced as lines after importing the point clouds provided by the photogrammetric capture into the BIM software.

The comparison of all the outputs of the Preliminary Knowledge Framework (A) and the Reverse Engineering (B) enhances the identification of previous transformations and interventions, the material-constructive characterization and decay mapping, such information to be included into the parametric model (C). This set of attributes is inherent to constructional and material features, description of decay patterns, report and motivation of the previous interventions, useful to semantically enrich the model.

Then, the Information Management (D) concerns the creation of an Information System integrating the three-dimensional model and external databases via ODBC tools (Open Database Connectivity). The Naviworks® Manage software has been tested for the management of the "as-built/as-damaged" HBIM model, as it is a BIM tool for viewing and managing information systems, despite being created for cost and time coordination; moreover, it supports the control of database and the data management via Structured Query Language (SQL).

The BIM model has been exported as *.nwd from Autodesk® Revit® to Navisworks® Manage, in order to have the possibility of simultaneously modifying the models in both the software products.

In Navisworks®, the building objects are firstly structured by macrogroups, distinct one from another according to the related construction phase and previous intervention, thus involving the time parameter (Sub-section 4.1).

Subsequently, each macrogroup has been matched to the categories of properties ('External Database Links', n.d.). These categories of properties can be manually added or automatically inserted linking external databases. The proposed information system connects the geometric HBIM model to external relational database, which were created as Excel spreadsheets or exported from the HBIM model, through the database management tools and compatible with the ODBC Driver of the employed multi-model-based management system. Indeed, Autodesk® Revit® permits the export of object parameters as external database via database management tools (i.e. the Ideate BIM link plug-ins ('Ideate BIM Link Software', n.d.), Revit DB link ('Access Autodesk Revit DB Link', n.d.), and the export tools embedded in the software.

The link of external databases into Navisworks® occurs with the configuration of the database via ODBC Driver, the Application Program Interface (API) for accessing the Database Management Systems (DBMS) within the "Datatools" plug-in. The user interacts with the relational databases via the Structured Query language (SQL), as it is the API for the Relational Database Management Systems (RDBMS). SQL statements are employed for queries of information from a relational database and for gathering data for reports. The SQL string *SELECT*from[Properties$]where"Element ID" =%prop("Element ID","Value")* matches the external database to the object in the model; the data fields correspond to the properties shown in the tables automatically created. The tables are organized in i) constructive macro-elements, ii) previous interventions and iii) description of crack patterns, introducing parameters, their description and data type (Sub-section 4.1)

Moreover, a more accurate "as-built/as-damaged" HBIM could be created through the integration of the parametric model with 3D photo-reconstruction (textured mesh) as an URL attribute of the used web viewer Sketchfab®. The URL generated in the web viewer can be linked in the BIM Information Management software Navisworks® Manage.

The last step is the 4D-HBIMM simulation (E) in Navisworks® Manage. Each macrogroup of the "as-built/as-damaged" HBIM model was associated to its time parameter for representing constructive evolution and the current state of conservation in a time line. The 4D-HBIMM simulation of previous events and the correlation of related information could support the identification of the causes of current decay patterns associated to human interactions with the building.

3. Case of study

The proposed methodology is applied to an Augustinian Monastery in Trani (southern Italy), as it is considered representative of historic buildings that underwent transformations and refurbishment over time and in degraded conditions, some caused by the succession of constructive events and incoherent actions.

3.1. Preliminary information collection (A)

The construction of the former Augustinian Monastery (Trani, south of Italy) began in the 16th century. Afterwards, Augustinian monks, in accordance with requirements, concessions and financial resources, repeatedly expanded the building until the 18th century and it went through a series of demolitions, reconstructions, structural interventions and functional upgrading between 1809 and 1960. Nowadays, the building presents heterogeneous interior distribution, different constructive systems and conservation status. Inside, we can recognize (Figure 2):

1. Unit 1 (1530): six rooms on the first floor and four larger spaces on the ground floor, built by Augustinian monks;
2. Unit 2 (1640): six basement rooms and the corresponding ground floor;
3. Unit 3 (1754 -1757): elevation of the Unit 2 and the completion of the cloister and the spaces overlooking it.

The aim of the previous interventions was the functional upgrade; the stratification of these interventions is still recognizable. In 1847, the monastery was converted into a hospital. After the abandonment in 1969, the building underwent a series of structural interventions and maintenance of foundations, roofs, façades because of serious settlements, not yet completely solved. In particular, the entire foundation has been reinforced with an underpinning made up of piles in order to solve the settling of primary rotation of the external façades, caused by heterogeneous foundations and soil. The kinematic movement is more complex where the units around the cloister. The low resistance of the soil, estimated by tests in 1992, and the demolition of some vaults replaced with hollow-clay/concrete slabs has jeopardized the static equilibrium (Petrignani and Camarchia 1992). Furthermore, the absent structural connection of the18th-century porch (Unit 3) and the 16th-century unit (Unit 1) contributed to the settling. In 2005, the continuous seepage of rainwater from the roofs caused damp spots on the main façade. Therefore, in 2007, some localized interventions were carried out concerning the cleaning of the main façades, the installation of the waterproof layer and the eradication of spontaneous vegetation. The corroded rebar of the concrete joist were rehabbed and the hollow-clay/concrete slabs consolidated by Fiber Reinforced Polymer (FRP) at the intrados (Fabozzi 2007).

3.2. Reverse Engineering (B)

The geometric survey has been carried out starting from the prior CAD and paper drawings integrated with photogrammetric acquisitions (Figure 3 (a), (b), (c)) applied on two rooms most representative of the building for the state of conservation and constructive technologies and accessible for using photogrammetry: a room of Unit 1 on the ground floor and the main stairwell. The use of UAV was neglected because the building is in the historic urban centre. The photographic set realized was carried out on the basis of an acquisition plan previously drawn up in order to optimize the survey time and ensure the effective overlap of 70% between the photographic shots. Photographic set of 164 shots for main stairwell and 330 shots for the room of Unit 1 have been acquired. The data processing of these images via

Agisoft Photoscan produced two dense point clouds (48.274 points for main stairwell and 75.155 points for the room of Unit 1) and two 3D-reconstruction models (texturized meshes) with a ground resolution of 0.994 mm/pixel at a distance of about 4 m away from the walls. Thus, the level of detail is high for displaying masonry texture and surface alterations. In addition, the visual inspection has been enhanced to glean typological and material information of masonry walls, floors, finishing, their state of conservation, observing the presence of crack paths and building pathologies. In the proposed method, the photogrammetric survey has supported an accurate modelling of geometries and decay patterns reaching the Level of Detail (LOD) 500 or LOG F, according to UNI 11337 (Brumana et al. 2017). Given the limitation of parametric modelling to the realistic reproduction of irregular geometries and deformations, typical of a historical building, was chosen to link a hyperlink of the 3D Photo Reconstruction Model -obtained from the point cloud - to the HBIM model. Hence, it is possible to preserve the geometric complexity.

3.3. "As-built/as-damaged" HBIM (C)

The "as-built/as-damaged" HBIM has been modelled in Autodesk® Revit® employing the point clouds for the two rooms mentioned before (Sub-section 3.2), and the existing 2D drawings for the rest of the building. In Figure 4 the photo and the parametric model of the whole building. The point cloud was imported into the family editor (*.sat) and used as a metric reference for the graphic representation of the decay pattern, vaults, doorways, widows and stair ramp. The building components (arched openings, barrel vaults, rib vaults, groin vaults, frames) and decay patterns (cracks and damp paths) have been modelled as BIM parametric objects, mostly customized. The as-damaged model is also the result of the modelling and the data enrichment of damp and crack patterns. Figure 5 shows the digital, parametric and computable representation of semi-parabolic cracks due to primary rotation and compared to the point cloud from which the BIM object was generated (Bruno et al. 2017).

The creation of the specific parametric object allows the insertion of geometric and descriptive attributes, derived from the analysis of information and data acquired during phase A and B of the methodology. As anticipated in Section 2, after importing in Navisworks®, the parametric objects have been grouped in six macro-categories divided by constructive epochs:1. First construction unit 1530 (Unit 1); 2. Building extension in 1640 (Unit 2); 3. Building extension in 1754-1757 (Unit 3); 4. Transformation in 1847-1969; 5. Intervention in 1992; 6. Intervention in 2007. Information added to each group concerns technical properties of the building components and historical/analytical features, and organized in the categories, as shown in Table 1, Table 2, Table 3.

4. Results and discussion

As mentioned in Section 2. Methodology, the former phases are propaedeutic to the Information Management (D) and the 4D-HBIMM simulation (E), structured activities with the aim of querying the databases for supporting the diagnosis.

4.1. Information Management (D)

The automatic export as ODBC Databases from the parametric model was made possible due to the BIM tools for Database Management (i.e. the Ideate BIM link plug-ins, Revit DB link, and the export tools embedded in the software). The use of Database arises from the possibility to manage information in software such as Excel or Access, or imported into other BIM software and their related plug-ins, thus facilitating Information Management (D).

Specifically, tables were created per each of the subsequent categories and properties, as described in Sub-section 3.3 and shown in Table 4.

As mentioned in Sub-section 3.2, the 3D photo-reconstruction model is linked to the HBIM model because it provides the actual knowledge (in situ and remotely) about the geometries, the decay condition and any decorated surfaces for documentation, structural monitoring and analysis of technological building systems (Garagnani and Manferdini 2013).

Then, the SQL Language permits consulting information within the information system through i) the selection of the interested building constructional group in the model and opening the related properties table (Figure 6) or ii) employing the conditional query operations to filter categories and properties, consequently comparing corresponding values (Figure 7). The difference between the two methods stands in the type and the quantity of properties. The first permits the view of all the information related to an object or to a group, the second one helps the filtering of the required properties per each category and the comparison of the values for specific analysis (i.e. diagnosis of a settlement).

In particular, in the first method (Figure 6), the selection of a BIM object in the group elements Unit 1 (1530) opens the properties table about the category "Analysis of the conservation state A_2017", reporting information about geometry, constructive techniques, interventions and transformations, crack patterns and settlements (properties in Tab 1). This operation can be executed per each element belonging to the subsequent transformations and interventions.

The second method (Figure 7) is the inverse process of the former one, because of the selection and correlation of the property to the element, highlighted in the model. The query operation permits the filtering of multiple data to be compared; the comparison of the detected settlings in each construction unit, the morphology of the cracks, and the motivation of the consolidation intervention. The query of the database, as set in Figure 7, underlines the presence of the same settlement in the three construction units: primary rotation of the external facades and this kinematic movement provokes the depression of keystone of the vaults of adjacent rooms.

4.2. 4D-HBIMM simulation

The correlation of the years in which occurred the first construction and subsequent transformations to each modelled constructive unit permits the 4D-HBIMM simulation in order to dynamically show the entire building life cycle to the actors of the refurbishment process (Figure 8). The problem in allocating the temporal parameter is the limitation that Navisworks® starts from 1753; thus, an ideal year has been assigned to each element, respecting the chronological order of the events.

The simulation allows an overview of the current conservation state, the constructive evolution and it is a support for diagnostic operations of the causes of decay and settlements. In Figure 7, the cracking pattern of three rooms of the building, two on the ground floor (a) and (b), and one on the first floor (c).

An analysis of the overall crack patterns reveals a primary rotation of the façade, and the simulation highlights the cause of the crack location and its morphology. Indeed, the facade was built during the expansion of 1754-1757, in addition to the already existing building core which includes the rooms on the ground floor. Therefore, it emerges that the wall is not tied to the pre-existing structure, thus cracks are visible between the floor and wall, but this problem is not present on the first floor, where the crack is on the wall orthogonal to the façade. On the other hand, the cracks in the vaults intrados can be traced back to the fact that the primary rotation is causing a separation of the vault abutments, with the consequence of scarce load equilibrium. The simulation also reveals that the static consolidation of foundations through a sub-foundation with piles has delayed the ongoing instability, not fully resolved.

4.3. 4D-HBIMM experimentation in comparison to traditional practice

Against the outcomes of the literature review in Section. 1.4, the proposed 4D-HBIMM methodology demonstrates potentiality in supporting diagnosis of actual causes, employing the information management and retrieval capability of BIM as it is database system of tangible and intangible information and data.

Firstly, the 3D representation of geometry and constructive evolution about historic building solves the limitations of traditional practices threatened by the fragmentation of the knowledge system that is extremely heterogeneous in terms of chronology, form, style and structure (texts, paintings, engravings, old photographs, maps, etc.), because reported in paper or digital formats. Therefore, it was necessary to establish a useful workflow to sort and condense multi-source data for current and future management, which allows easy updating of data and collating previous and future geometric and non-geometric information. In this regard, the 4D-HBIMM overcomes the issues of traditional practices in i) investing a lot of time in the retrieval of documents, the survey of current building condition, ii) coordinating of the figures involved in the process and iii) consulting separate paper and digital documents about the geometric asset and incremental knowledge about the building that leads to errors.

Secondly, it is an evolution of the approached employed by Rodríguez-Moreno et al. 2016 (Rodríguez-Moreno et al. 2016) because it utilizes semi-automatic procedures based on the integration of the 3D model and structured databases and the inserted data/information sets can be compared with query operations. The databases are organized according with the historical flow via time parameter, useful for the study and analysis of the past and the prevention of possible risks in the future.

Finally, the navigation of the building history and state of conservation could be immediately managed thanks to the hierarchization of the construction elements featured by relational databases. The digital managing has the benefit of facilitating a comparison of graphical and no-graphical information; for example, the direct connection of the instabilities detected within the building nucleuses, the morphology of the cracks and the related causes conducts to the identification of the consolidation interventions.

5. Conclusions and future developments

The HBIM methodology demonstrates potentiality in aggregating information and data from archival, bibliographic sources, memories, traditions, surveys, but advances are required for automatic analysis of this knowledge in order to support the diagnosis of actual causes employing the information management and retrieval capability of BIM. It could be used as an initial guideline to organize maintenance and conservation interventions, as it is a digital archive for historical documentation, survey data, diagnostics and monitoring. This article proposes the 4D-HBIMM system, an innovative methodology for managing knowledge about historic buildings assembling an interoperable workflow of existing commercial BIM tools. The connection of the HBIM model with external databases makes the historical evolution more comprehensible to all the users. The implementation of programs with query languages allows feasible access of data in the database. The SQL (Structured Query Language) is a common programming tool used by relational databases as the BIM ones for searching the required information. An advantage of this methodology lies in the assembly of easy-to-use software products with simple scripting for databases.

The effectiveness of the method stands in the organization of the BIM model in groups of BIM objects corresponding to each identified constructive phases - each one associated to a timeline - and the structuration of the related knowledge in order to facilitate the query and analysis for diagnosis. In particular, the properties are associated to each parametric group about each temporal phase. Firstly, the categories collect the data/information about i) the analysis of the state of conservation, as executed per each constructive unit, ii) previous consolidation interventions and iii) the current decay patterns. Then, the properties are defined as alpha-numerical parameters per each category, assigning a description and a data type. Such a system, characterized by an easy user-interface, can automatically produce the

4D-HBIMM simulation that consists of the reproduction of the entire building life cycle and the query of properties.

The benefit of the Information Management is the support in identifying settling causes via database queries, consequently suggesting adequate interventions.

Thus, the 4D-HBIMM system will support public and private actors such as building managers, planners, construction companies, researchers and users in the refurbishment process from the knowledge phase to the conservative interventions/maintenance and in the management of funding according to the current building conservation conditions.

This methodology has been tested on a case study and it can be applied on several historic buildings. The Reverse Engineering and "as-built/as-damaged" HBIM steps can be planned and performed with other methods according to the environmental conditions and morphological features of the building itself. In recent literature, accuracy and quality of the 3D models is evaluated with methodologies based on semi-automatic procedures (Daniel Antón , Benachir Medjdoub 2018). In this case study, the objective was not the accurate generation of the geometric model, but the semantic enrichment and an efficient management and analysis of non-graphical information. For this reason, the modelling step can be refined in order to achieve a rigorous HBIM model. Nevertheless, remaining within the main research objective, the link between the parametric model and 3D photo-reconstructed model (texturized mesh) allows to gain an accurate understanding of three-dimensional geometry and surfaces. This geometric model is sufficient for aggregating archival and bibliographic sources, memories, traditions, systematic diagnostic and monitoring activities aiming at complete material and constructive characterization and assessment of the level of degradation. However, further efforts may be performed for the automation of the recognition and the modelling of different constructive elements and decay patterns starting from the 3D photo-reconstructed models and meshes, in order to reinforce the entire HBIM methodology.

Future development will also consist of the integration of database about past execution techniques related to each architectural component, another aspect that can be the cause of decay and settlings. Moreover, further research could identify a method for the automatic diagnosis of causes and the suggestion of intervention hypotheses through the collation and the logic correlation of data and information. Finally, the problems related to the use of large files could be overcome through the development of web-based services in the cloud that can ensure the same operative framework of the proposed 4D-HBIMM method.

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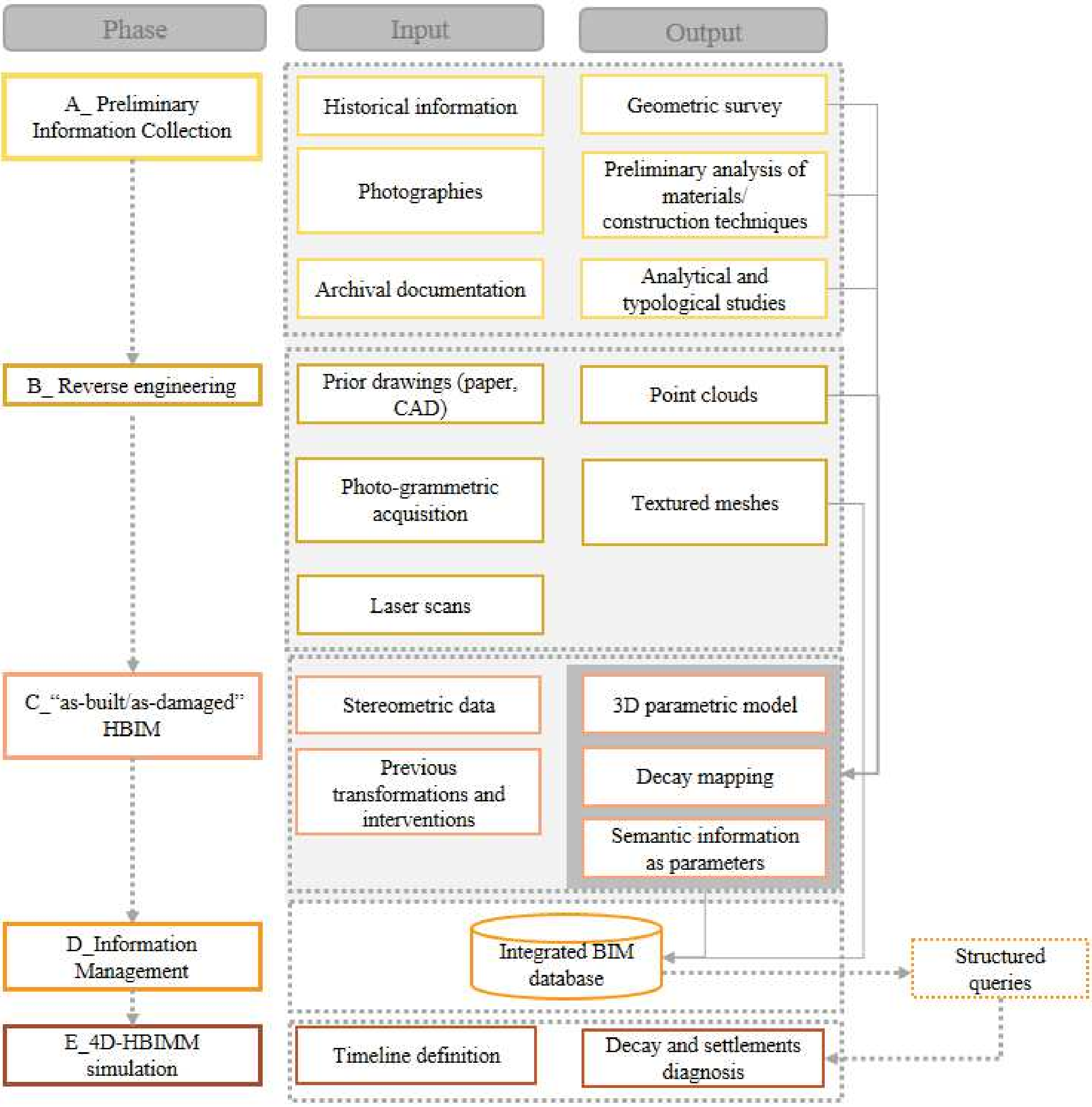

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798 Figure 1 Operative method scheme

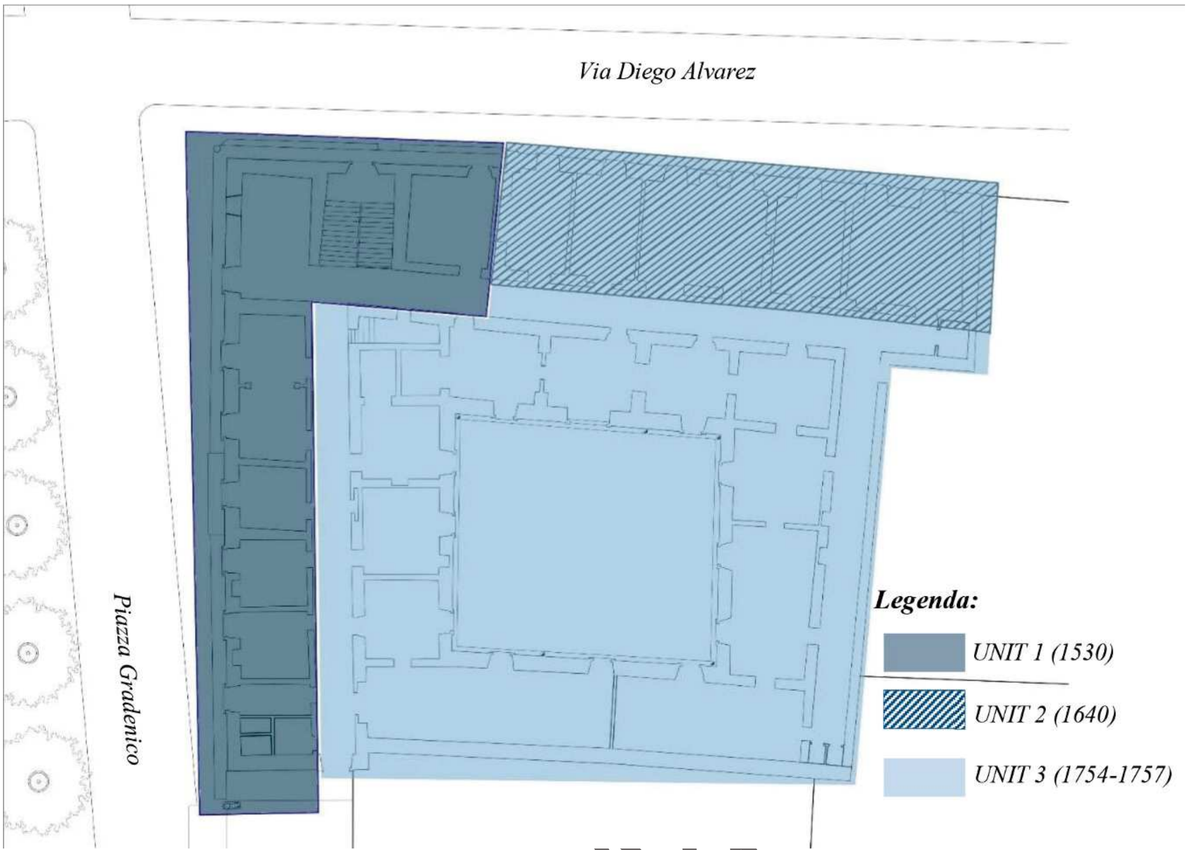
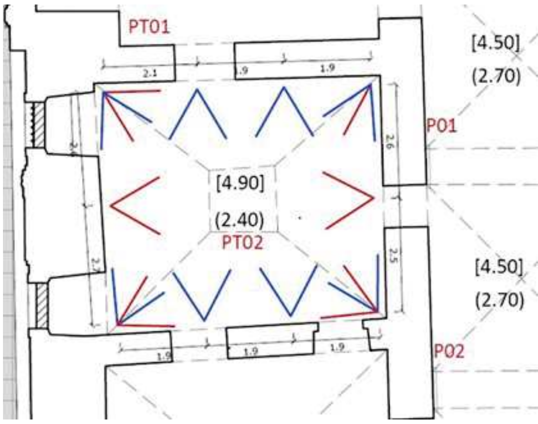


Figure 2 Transformations over time (Unit 1, 2 and 3)

(a) (b)



(c)

Figure 3 (a) Acquisition plan, (b), Frame, (c) Texture mesh

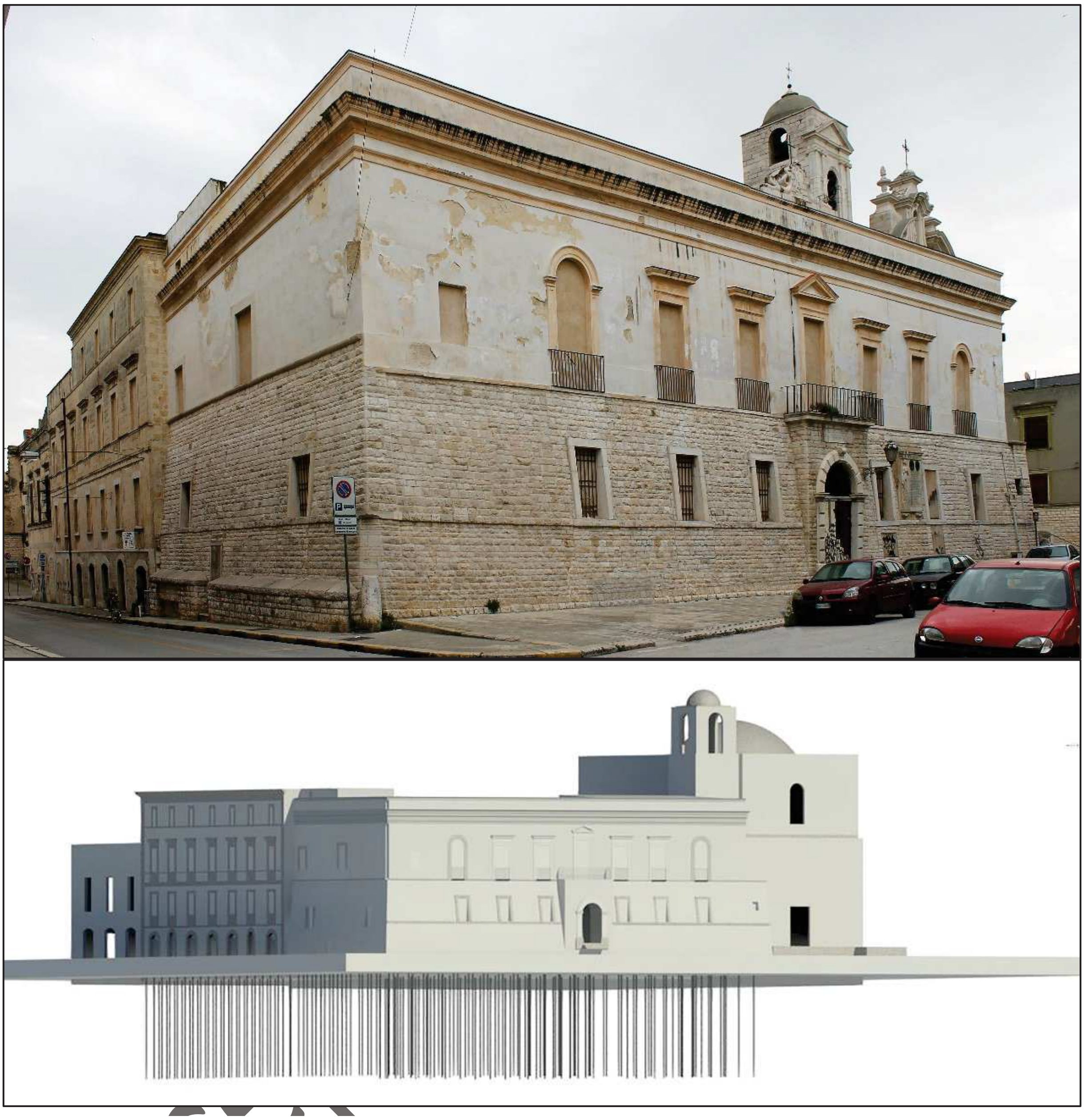
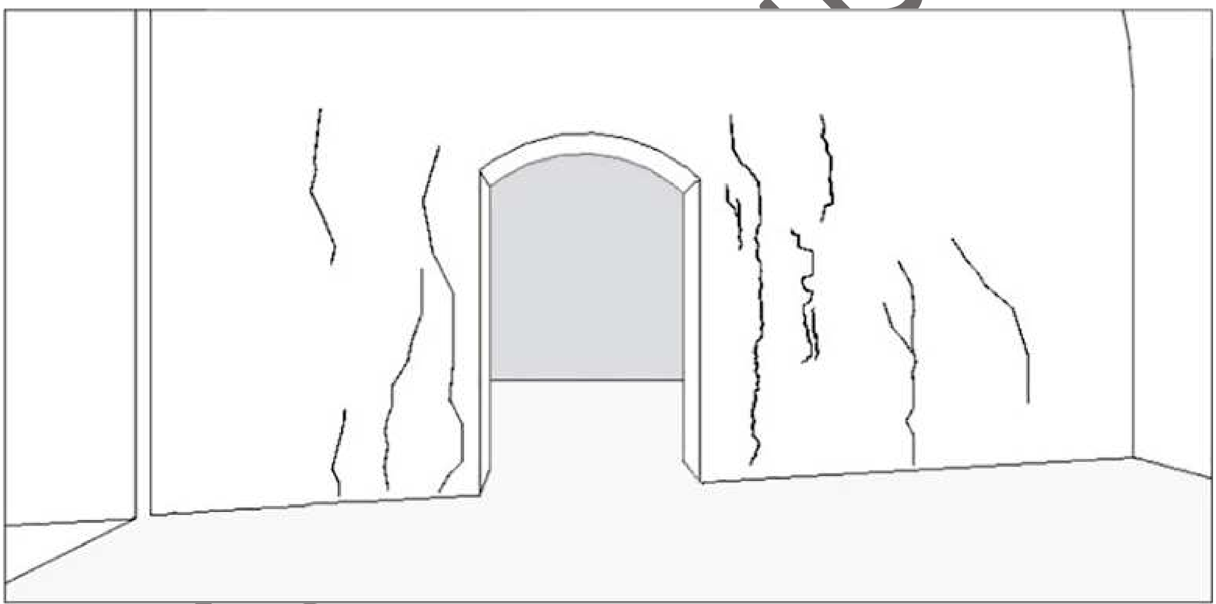


Figure 4 Comparison between photo and parametric model

(a)



(b)

Figure 5 (a) Point cloud (b) HBIM model as-damaged

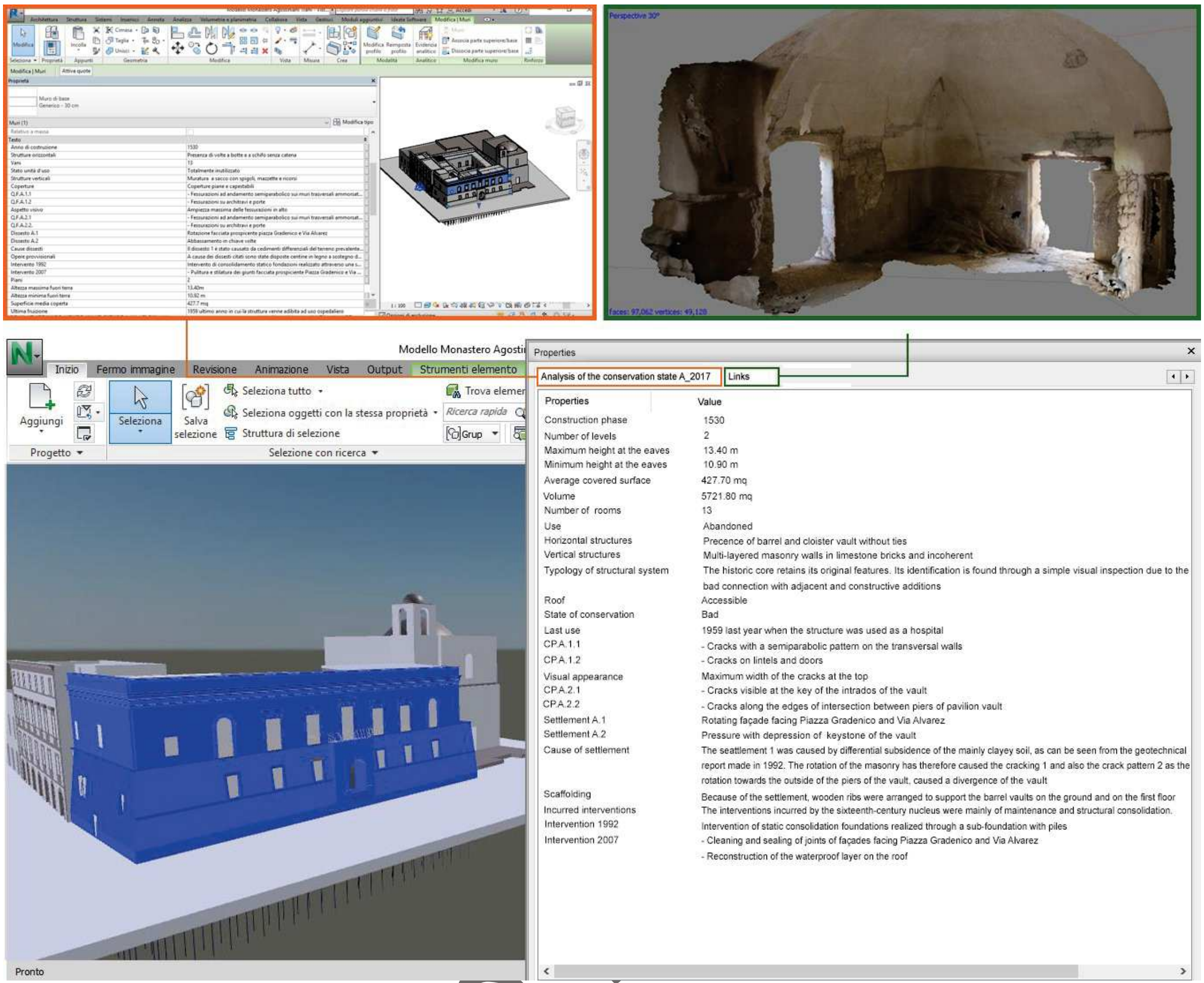


Figure 6 Integrated BIM database

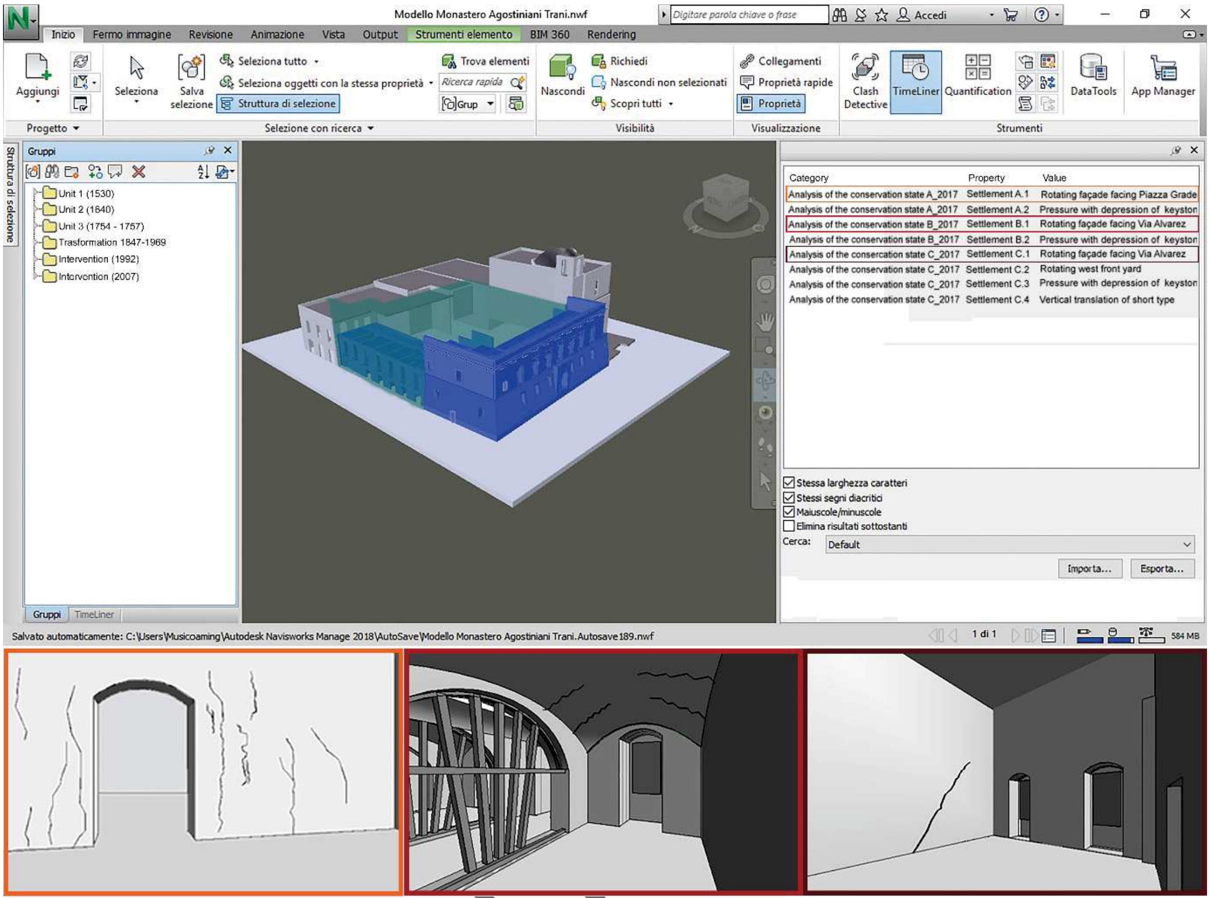


Figure 7 Selection of categories, property to be analysed, query and property value of the tree units. Down the cracking pattern of three rooms of the building, two on the ground floor (a) Unit 1 and (b) Unit 2, and one on the first floor (c) Unit 3.

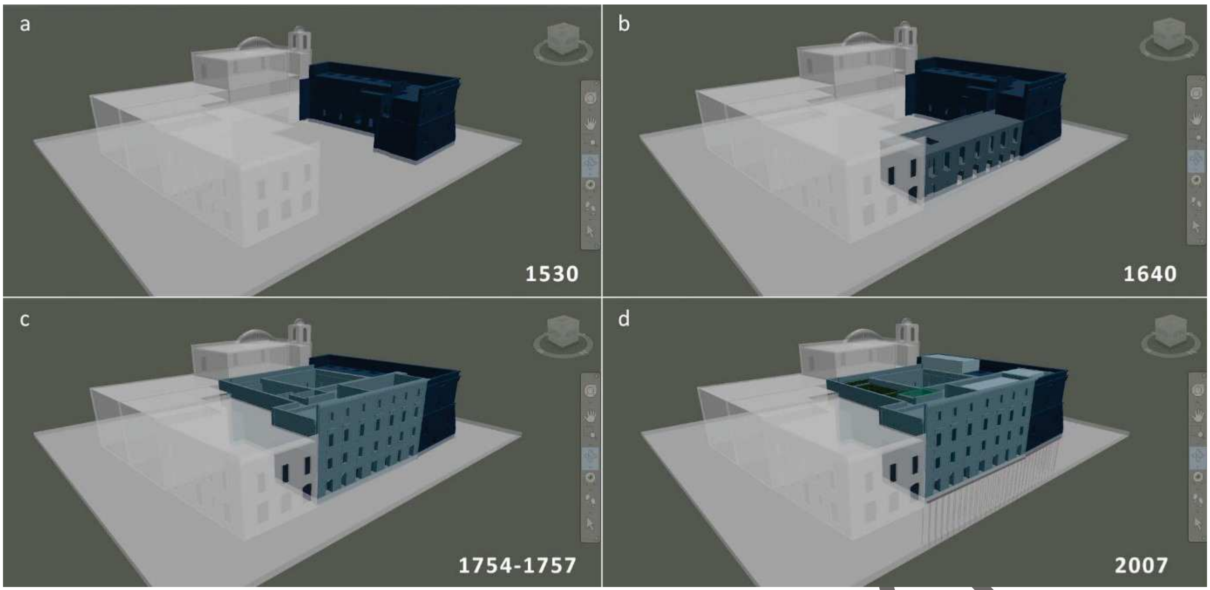


Figure 8 Simulation of constructive phases

Table 1 Parameters about data Unit 1, Unit 2 and Unit 3

CONSTRUCTIVE MACRO-COMPONENTS		
Parameters	**Description**	**Data Type**
Construction phase	Year of constructive macro-component (Unit 1, Unit 2, Unit 3).	NUMBER
Number of levels	Number of floors in the macro-component.	NUMBER
Maximum height at the eaves	Dimension expressed in meters.	NUMBER
Minimum height at the eaves	Dimension expressed in meters.	NUMBER
Average covered surface	Dimension expressed in square meters.	NUMBER
Volume	Dimension expressed in cubic meters.	NUMBER
Number of rooms	Number of rooms that composes the constructive nucleus.	NUMBER
Use	Use of the rooms that composes the constructive nucleus.	MULTILINE TEXT
Horizontal structural systems	Constructive system of horizontal structural systems (technical typology of vault, slab, etc.).	MULTILINE TEXT
Vertical structural systems	Constructive system of vertical structures (wall).	MULTILINE TEXT
Typology of structural system	Description of structural system (load-bearing masonry, reinforced concrete beams and columns).	MULTILINE TEXT
Roof	Typology of roof.	MULTILINE TEXT
State of conservation	Comments about the state of conservation based on visual inspection.	MULTILINE TEXT
Last use	Indication of the last designated use of the building	MULTILINE TEXT
CP X.N.	Crack Pattern (CP), description of morphology of a crack patterns (N) related to the constructive nucleus (X=1,2,3).	MULTILINE TEXT
Visual appearance	Description about the visual appearance of crack patterns.	MULTILINE TEXT

Settlement X.N.	General description of the settlement related to CP.X.N .	MULTILINE TEXT
Causes settlement X.N.	Description of the causes of settlement X.N	MULTILINE TEXT
Scaffolding	Typological and material description of scaffolding in the constructive nucleus.	MULTILINE TEXT
Incurred interventions	List of incurred interventions to constructive nucleus.	MULTILINE TEXT
Intervention 1992	Description of the intervention.	MULTILINE TEXT
Intervention 2007	Description of the intervention.	MULTILINE TEXT

Table 2 Parameters about previous interventions: Transformation in 1847-1969; Intervention in 1992, Intervention in 2007

Previous interventions		
Parameters	**Description**	**Data Type**
Year of intervention	The year of construction of the nucleus.	NUMBER
Accessibility by inspection	Possibility of inspection of the intervention.	MULTILINE TEXT
Typology of intervention	Description about typology of intervention.	MULTILINE TEXT
State of conservation	Comments about the state of conservation based on visual inspection.	MULTILINE TEXT
Settlement prior intervention	Description of Settlement X.N related to CP.X.N.	MULTILINE TEXT
Causes of intervention	Description of the motivation for Settlement X.N.	MULTILINE TEXT
Description of intervention	Description of intervention (phases, materials, constructive techniques).	MULTILINE TEXT
Piles foundation system	Material and dimensional composition of piles foundation.	MULTILINE TEXT
Source of file	Indication about source of files and information.	MULTILINE TEXT

Table 3 Parameters about crack pattern

description of crack patterns		
Parameters	**Description**	**Data Type**
Encoding host	Code of constructive element where the cracking is identified.	MULTILINE TEXT
Crack pattern typology	Typology of the crack pattern.	MULTILINE TEXT
Settlement	Description of settlement.	MULTILINE TEXT
Cause of settlement	Description of the causes of settlement.	MULTILINE TEXT
Crack length	Dimension computed along the vertical axis, orthogonal to the floor.	MULTILINE TEXT
Crack upper cusp dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack lower cusp dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack skirt dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack description	Morphological description of the crack (vertical, horizontal, parabolic shape, etc.).	MULTILINE TEXT
Crack progression	Indication about the progress of the cracking.	MULTILINE TEXT
Edges profile	Indication of visual appearance of edges profile (sharp edges, rounded edges).	MULTILINE TEXT
Monitoring system	Indication about monitoring activities (optic fibers, strain gauges, etc.).	MULTILINE TEXT

Table 4 Correlation among constructive evolution, category of transformation/interventions and tables of properties

Transformation	**Category**	**Properties**
Unit 1(1530)	Analysis of the conservation state A_2017	Tab 1
Unit 2 (1640)	Analysis of the conservation state B_2017	
Unit 3 (1754-1757)	Analysis of conservation state C_2017	
structural consolidation of foundation	Intervention in1992	Tab 2
rainwater penetration solutions	Intervention in 2007	
Current decay state: Crack patterns. The model also presents a hypertextual link to the texturized 3D mesh (Sub-section 4.2).	Analysis of the conservation state X_2017	Tab 3