remote sensing

MDPI

Article

An Efficient Process for the Management of the Deterioration and Conservation of Architectural Heritage: The HBIM Project of the Duomo of Molfetta (Italy)

Enrique Nieto-Julián [1,*], Silvana Bruno [2] and Juan Moyano [1]

[1] TEP970 Group Technological Innovation, 3D Modelling and Diagnosis Systems in Heritage and Building, Department of Graphic Expression and Building Engineering, Universidad de Sevilla, 41004 Seville, Spain; jmoyano@us.es

[2] Department of Civil, Environmental, Land, Construction and Chemistry, University Polytechnic of Bari, 70126 Bari, Italy; silvana.bruno@poliba.it

* Correspondence: jenieto@us.es; Tel.: +34-654267425

Abstract: The work developed aims to present an innovative methodology to execute the heritage conservation processes in a collaborative and interdisciplinary Building Information Modeling (BIM) project, with an effective management of the deterioration suffered over time, emphasizing the structures and coatings. The research begins with an architectural survey using terrestrial laser scanning (TLS) and terrestrial photogrammetry software, Structure from Motion (SfM), studying study the Duomo of Molfetta (Italy), a unique Romanesque architecture of Puglia (Italy). The methodological process is mainly aided by the precise semantic segmentation of global point clouds, a semi-automatic process assisted by classification algorithms implemented in the Cyclone 3DR post-processing software, which has allowed the classification of the unstructured information provided by the remote sensing equipment when identifying the architectural-structural systems of a building with high historical values. Subsequently, it was possible to develop an efficient Scan-to-HBIM workflow, where the Heritage BIM (HBIM) project has fulfilled the function of a database by incorporating and organizing all the information (graphic and non-graphic) to optimize the tasks of auscultation, identification, classification, and quantification and, in turn, facilitating the parametric modeling of unique structures and architectural elements. The results have shown great effectiveness in the processes of characterization of architectural heritage, focusing on the deformations and deterioration of the masonry in columns and pilasters. To make multidisciplinary conservation work more flexible, specific properties have been created for the identification and analysis of the degradation detected in the structures, with the HBIM project constituting a manager of the control and inspection activities. The restoration technician interacts with the determined 3D element to mark the "type decay", managing the properties in the element's own definition window. Interactive schemes have been defined that incorporate the items for the mapping of the elements, as well as particular properties of a conservation process (intervention, control, and maintenance). All listed parametric elements have links to be viewed in 2D and 3D views. Therefore, the procedure has facilitated the auscultation of the scanned element as it is semantically delimited, the parametric modeling of it, the analytical study of its materials and deterioration, and the association of intrinsic parameters so that they can be evaluated by all the intervening agents. But there are still some difficulties for the automatic interpretation of 3D point cloud data, related to specific systems of the historical architecture. In conclusion, human action and interpretation continues to be a fundamental pillar to achieve precise results in a heritage environment.

Keywords: architectural heritage; conservation; Duomo of Molfetta; deterioration of masonry; HBIM; semantic segmentation; scan-to-BIM

check for updates

Citation: Nieto-Julián, E.; Bruno, S.; Moyano, J. An Efficient Process for the Management of the Deterioration and Conservation of Architectural Heritage: The HBIM Project of the Duomo of Molfetta (Italy). *Remote Sens.* **2024**, *16*, 4542. https://doi.org/10.3390/rs16234542

Academic Editors: Rui Marques, Claudia Mondelli and Maria Giovanna Masciotta

Received: 8 August 2024
Revised: 22 November 2024
Accepted: 26 November 2024
Published: 4 December 2024

1. Introduction

Every form of sculptural and graphic expression, whether artistic or architectural, carries with it the principles of semiotics and semantics. Semiotics in architecture refer to the analysis of the symbolic and significant aspects of architecture. The discipline of architectural surveying, accompanied by a scientific and technical methodology, guides the scientific knowledge of the works, as well as their form and context [1]. The study of heritage refers to the past in its context of the inheritance received, and technology represents the contribution to a future to come. In this framework, 3D modeling aims to contain and reflect the uniqueness of geometry, considering the structural deformations and construction properties they acquire throughout their life cycle.

The geometry of cultural heritage (CH) is captured by technology procedures that have to do with engineering and geomatics, which have become a common practice, such as digital terrestrial photogrammetry (DTP), photogrammetry with unmanned aerial vehicles (UAVs), together with the photogrammetric process by Structure from Motion (SfM), and technology by terrestrial laser scanning (TLS) for 3D digital reconstruction [2]. The current research agenda recommends the need for an interpretation of the set of 3D points, with the aim of identifying and quantifying patterns of elements from the decomposition of the elements, looking for functionality, semantics, and topology [3]. To help conserve and document CH, researchers are also implementing multiple prospecting techniques at once, such as [4], which include the "Digital Single Lens Reflex" (DSLR) camera and TLS for indoor and outdoor studios, merging active and passive sensors; Ref. [5] used TLS and DTP to achieve detailed and accurate representations; others performed comprehensive surveys of DSLRs, UAVs, and TLS cameras [6]; Ref. [7] performed rapid photogrammetric surveys using a Nikon D800E DSLR; and Ref. [8] applied DTP and Spherical Photogrammetry (SP) for data representation and enrichment.

Moreover, Artificial Intelligence (AI) is playing an important role in the preservation and study of CH with a view to automating processes; it is used in the conservation and restoration of architectural heritage in various ways, such as virtual reconstruction of historic buildings, image scanning and recognition, remote sensing, and degradation prediction for preventive conservation. In the field of remote sensing, major advances in image matching algorithms are changing the landscape of 3D architectural and archeological reconstruction. In addition, with the arrival of new geomatic technology equipment, such as the personal mobile laser scanner (PLS), data capture in the measurements of architectural spaces is simplified [9]. The innovative integration and combination of TLS equipment with aerial Light Detection and Ranging (LiDAR), such as drone-mounted scanners, is one of the most cost-effective solutions that can provide spatial data. This approach significantly reduces the time and resources required to carry out surveys and mappings, resulting in significant cost and time savings [10]. Among the most prominent are the DJI Matrice 300 RTK Zenmuse L1 UAV, developed by Da-Jiang Innovations Science and Technology, Shenzhen, China, used in forestry studies [11], and the Leica Geosystems BLK2GO scanner that captures moving images [12]. Each of the aforementioned techniques is associated with the registration space that is intended to be obtained. Once the record is obtained and the data processing is complete, the result is an unclassified set of points. Therefore, the great challenge for the scientific community is to have procedures for classifying complex elements in architecture and archeology, as evidenced in the following Section 2—Literature Review. This classification is valid for processing data in current BIM methodologies that allow interdisciplinary collaboration and the combination of compliance verification and analysis tools. In this sense, segmentation is a process of point cloud classification for the identification of homogeneous areas or entities that have similar characteristics, let us call them point cloud attributes with a semantics. But currently one of the challenges is to manage and process all that data so that they have basic functionality, not only in 3D digital models, but also in the applicability of the Historic Building Information Model (HBIM) environment [9].

Objective

The main objective set in this research is to develop an efficient and interoperable methodological process from scanning to BIM in a conservation process, which enables a reduction in the existing shortcomings in multidisciplinary projects of intervention in architectural and artistic heritage. Since it is crucial to capture the spatial and metric description of the container and content of the historic building, it is intended that the information can be a substantial basis for obtaining the temporal construction semantics, transformed by the passage of time, and that it serves to analyze deterioration, pathologies, and those other problems detected in the structures that complicate the stability of the building. Developing the process in a BIM environment implies having a faithful, identified, and classified geometric representation, which will facilitate the interoperability of data between specialists: architect, archeologist, historian, engineers, restorer, and the property.

2. Literature Review

Since its origins, remote sensing has continued to be implemented progressively and effectively in many research fields, bringing many benefits for the automation and management of the data captured. Among the diversity of techniques, we find synthetic aperture radar interferometry (InSAR), an advanced technique that uses radar data obtained from satellites or ground systems to measure deformations with high precision, both on the earth's surface and in buildings, to be effective. InSAR compares two or more SAR images taken from similar positions but at different times, being able to detect millimetric changes in the height of the terrain or in structures. Its integration with other technologies, such as terrestrial laser scanning (TLS) and finite element modeling (FEM), amplifies its efficiency and interpretability. The authors of [13] perform an integration of GB-InSAR and TLS to obtain 3D representations of deformations, which is very useful for the early detection of anomalies and the evaluation of the impact of human activities on masonry. Refs. [14,15] highlight its applicability in large archeological areas to identify potential risks, while [16] address structural deformations in wide geographical areas, employing InSAR for the analysis of damage by differential settlements using heritage databases and analytical models. More recent studies [17] use LSTM neural networks to predict settlements based on SBAS-InSAR data, aiding in early decision-making and risk mitigation in the protection of architectural heritage.

The scientific community continues to be very intensely involved in the efficient management of the data provided by remote sensing systems, complemented by photogrammetric and scanning data, since the 3D information provided through large numbers of points or point clouds (PCs) is usually very valuable, which in the case of architectural heritage is essential to efficiently document and analyze its state of conservation.

2.1. Remote Sensing by 3D Point Clouds in Heritage

PCs allow an agile and detailed assessment of the structural condition of the historic building, reducing laborious "on-site" inspections [18], and provide precise information on the texture and geometry of the surfaces, scanned or photographed, which can then be analyzed to identify damage to the structures [19].

Laser scanning and photogrammetry are appropriate for covering large heritage sectors, reducing the time of auscultation and taking measurements, which makes them very efficient technologies in places that are difficult to access [20]. The post-processed information provided (PCs) facilitates the documentation and analysis of sites located in very heterogeneous environmental conditions and in places inaccessible by more traditional methods, which helps in inspection and monitoring tasks [21]. Both the acquisition and analysis of collected data prove to be faster and less expensive compared to traditional inspection and measurement methods [22]. Another potential is the capture of minimal details and the exact identification of deteriorated surfaces, such as cracks, fractures, and loss of material, thus contributing to an adequate analysis of the structural condition [23] and the state of the coatings associated with the heritage elements.

2.2. Detection of Deterioration

Automating the process of detection and semantic segmentation of deteriorated surfaces of heritage buildings based on the study and management of PCs, acquired through photogrammetric and TLS techniques, and their implementation in the modeling of heritage building information (HBIM), is nowadays a priority for a large number of researchers. The aim is to improve manual and time-consuming procedures, replacing them with efficient and precise automatic processes that support architectural heritage conservation efforts. The most autonomous segmentation and classification are usually aided by unsupervised machine learning (ML) and deep learning methods, based on dynamic convolutional neural networks. The process involves the accurate recognition of architectural elements and accelerates the modeling of historic buildings for the development of the HBIM project [24]. ML methods and clustering techniques to automatically segment PCs can also help detect alterations in historical surfaces, such as color variations and biological colonization, based on color information from PCs [25]. The main objective of these methods is to automatically detect objects and data using specific algorithms to evaluate and monitor the condition of buildings and thus identify deteriorated surfaces. In parallel, these advanced techniques contribute to an accurate and rapid assessment of structural degradations, facilitating continuous monitoring and the development of effective conservation strategies [26]. Another benefit of PC segmentation is the improved performance of 3D data management platforms by reducing calculation time and increasing model accuracy [27]. In the specialized literature, various automatic systems have been developed for the detection of cracks and degradations. Ref. [28] uses the Gaussian Filter and the Random Sample Consensus (RANSAC) algorithm for the detection of the initial shape of the cracks. In [29] the authors have created a system that identifies cracks by using the Gaussian Filter, Intensity Gradient, and pattern detection. Ref. [30] proposes a semi-automatic detection method based on an image approach to identify degradations in facades. Nevertheless, some criticalities are encountered as the necessity of a large amount of training data to meliorate the accuracy of classification methods thus reaching a high precision in detecting architectural elements, and—above all—decay patterns.

Classification methods that are not aided by ML are also very effective [31] and therefore do not rely on extensive training datasets; they are mainly based on image processing techniques and detected geometric analysis. These methods have the great advantage of being flexible and efficient in terms of time, cost, and implementation, reducing the risk of overfitting [32]. For all these reasons, bearing in mind that the final objective of the research is the management of data intrinsic to the semantic and parametric elements of an HBIM model, the proposed methodological process is aided by a semi-automatic semantic segmentation, although more accessible and efficient. The operator's supervision will always ensure the accurate detection of deterioration in historic buildings.

2.3. Data Classification

Most segmentation studies use software external to the software used for processing. In these cases, they apply the RANSAC-based plane adjustment algorithm to add an additional layer of abstraction [3]. RANSAC is an iterative algorithm used to estimate the parameters of a mathematical model from a dataset containing a significant proportion of outliers. It was introduced by Fischler and Bolles in 1981 [33] and it has become a standard technique in computer vision, image processing, and point cloud. It is based on the idea of repeatedly selecting a random subset of the input data, fitting a model to this subset, and then evaluating how the model fits the entire dataset. RANSAC's key strength is its ability to cope with a high level of outliers in input data. Unlike traditional tuning methods that can be affected by outliers, this algorithm ignores outliers and focuses on most of the data that fits the model well [34]. Examples include the research that develops a classification based on model adjustments through the determination of geometric primitives, using the RANSAC algorithm and the Hough transform as classification processes. Dong et al., 2018 [35] conducted a segmentation classification based on four essential points using methods based on the growth of the region, which extract 3D planes by progressively merging adjacent points or voxels with similar characteristics [36], among others. Methods based on model fitting, which are most commonly used for plane segmentation (RANSAC) and Hough transform have successfully demonstrated 2D and 3D shapes. In later studies, there are methods based on function clustering, which characterize point clouds in primitives based on certain pre-calculated surface properties [37]. To this large set of studies on segmentation, the usefulness and functionality of classification procedures must be proposed. Many of the studies are dedicated to the classification of urban regions, others to interior spaces, the selection of objects, the elimination of noise in the point cloud, the classification of urban furniture, or also the creation of digital twins in the field of CH and morphological semantic segmentation [38].

Some research offers more advanced segmentations in architectural heritage as they implement machine learning in parametric BIM [39]. The process consists of the transition, still semi-automated, from unstructured TLS data to the semantically rich representation of buildings and historical H-BIM assets, applied mainly to recurrent architectural typologies that are supported by construction rules and/or building proportions, as is the case of a Renaissance loggia. The objective is to achieve an effective, precise, and productive interdisciplinary process that can be shared by architects, engineers, conservators and restorers to update, retrieve, and archive the available heritage information based on semantically enriched parametric models. For this reason, for the HBIM project of the Duomo di Molfetta, intelligent process automation is also sought, using, in this case, the classification algorithms implemented in various software tools [40] with the aim of simplifying the frequent tasks of management, point cloud classification, and reverse engineering thus reducing the times in the development of architectural projects, engineering, construction, and conservation (AECO).

2.4. The Scan-to-HBIM Process

If the above is analyzed, it is essential to combine the various techniques to achieve an efficient methodological process that takes advantage of each prospecting method to achieve the best conservation and documentation requirements. This is where the BIM methodology provides fundamental help to integrate the various conservation and documentation data (graphic and non-graphic) into a comprehensive historical construction model. The identification of geometric characterization in a Heritage BIM (HBIM) project is crucial for operators who are morphologically modeling architectural elements. The process initiated in Massive Data Capture Systems (MDCS) that involves the construction of 3D models with parametric objects, called Scan-to-BIM, presents great challenges due to the complexity of the historical architecture, always seeking to solve the errors of the BIM model according to a scanned work [41]. This is posed as the challenge of the construction of the ideal model and, on the other hand, of the deformations that arise on site, admissible by the technical teams of execution for the project. In architectural heritage, this difference between the ideal model and the real model becomes more and more pronounced as time goes by in the life cycle of old buildings, due to the deterioration of the elements. Therefore, the great challenge and scientific discussion focuses on the automatic position of capturing the structural deformations that can occur in an HBIM project. There are several scientific reviews of the combination of remote capture of information, such as 3D laser scanning, with BIM applications [42,43], where the dilemma of finding operators who can solve complex geometries is raised. The problem also arises that the manual process of constructing the geometry of a historic building from the point cloud is a process that requires a considerable amount of time, since it is necessary to structure the point cloud in parts and to make an efficient classification of the data [44] and eliminate those that are unnecessary, usually according to the criteria of the rehabilitator–operator. Another aspect that should be highlighted is the amount of information that is managed, since the point cloud has an important weight where BIM platforms must overcome and manage efficiently.

For all these reasons, the challenge of this research is to make a classification and semantic segmentation of the point cloud by architectural/structural typologies, facilitating the modeling and management of the HBIM project in the conservation process, and incorporating, in addition, the deformations and deterioration that the structural elements of the Duomo di Molfetta have suffered, both in their real geometric facet and in their analytical data. These peculiarities of a historic building, although they have been classified and analyzed under the environment of specialized engineering software (Cyclone 3DR 2023 Leica), are perfectly linked to the HBIM project (Archicad 27 Graphisoft).

3. Methodological Process

This study involves a deep knowledge of the historical architecture by applying a semantic segmentation of the point cloud and its processing in a common data environment managed from the HBIM project. The methodology is supported by a semi-automatic process assisted by algorithms that allows for classifying and segmenting the unstructured information provided by the TLS scanner to support the HBIM project. The Duomo di San Corrado, Molfetta (Italy), an example of Apulian Romanesque architecture and an emblematic representation of heritage, has been chosen for the study. The building was scanned in its entirety inside and main façade while photogrammetry covered the survey of the other facades.

The paper presents the results of a semantic segmentation method based on classification algorithms that are implemented in point cloud processing software, such as Cyclone 3DR from Leica Geosystems. A direct workflow is created with the BIM platform so that the fractions of points, already identified, are introduced into the HBIM project for classification, according to architectural typologies and construction systems. This fragmentation makes BIM parametric modeling more flexible. To cover the conservation phases, specific properties are created for the identification and analysis of the deterioration detected in the building structures, strengthening the work of analysis and control.

The methodological process reinforces the interoperability of the HBIM project data with conservation and restoration specialists at all times. A comparative analysis of some defects of the Duomo columns is carried out, comparing the TLS information with the theoretical parametric object. Finally, the HBIM project incorporates the deterioration located in the structures, associated with the real geometry of the parametric elements of the model, whether in the form of groups of points segmented by categories or as 3D mesh surfaces, all of them identified and classified; they have also been enriched with the technical reports obtained from the study of pathologies. The complete methodological process is illustrated in Figure 1, and a detailed description of each phase is reported in the paragraphs below.

3.1. Case Study

For the experimental study, a survey of the Duomo of Molfetta (Italy) was carried out using terrestrial laser scanning techniques. Built between 1150 and the end of the 13th century, the building is a unique example of Romanesque-Pugliese architecture (Figure 2a,b). With respect to the spatial configuration of its construction, it has an asymmetrical basilica floor plan, divided into three naves by cruciform pillars with inclined columns. The central nave has three domes, supported on a hexagonal drum. Of the large volumes, the roofs that cover the aforementioned vaults and the two bell towers that flank the main façade stand out (Figure 2c).

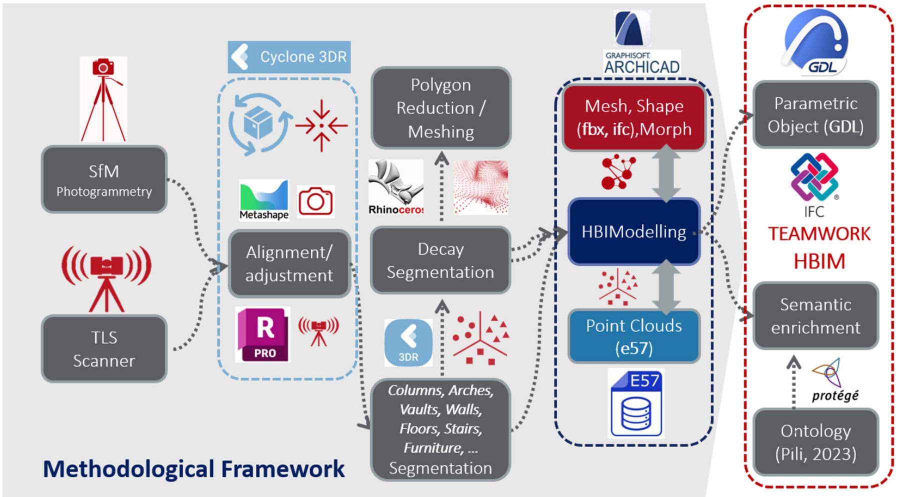


Figure 1. Methodological framework diagram. Implemented ontology by A. Pili, 2023. https://www.politesi.polimi.it/handle/10589/196392 (accessed on 25 November 2024).

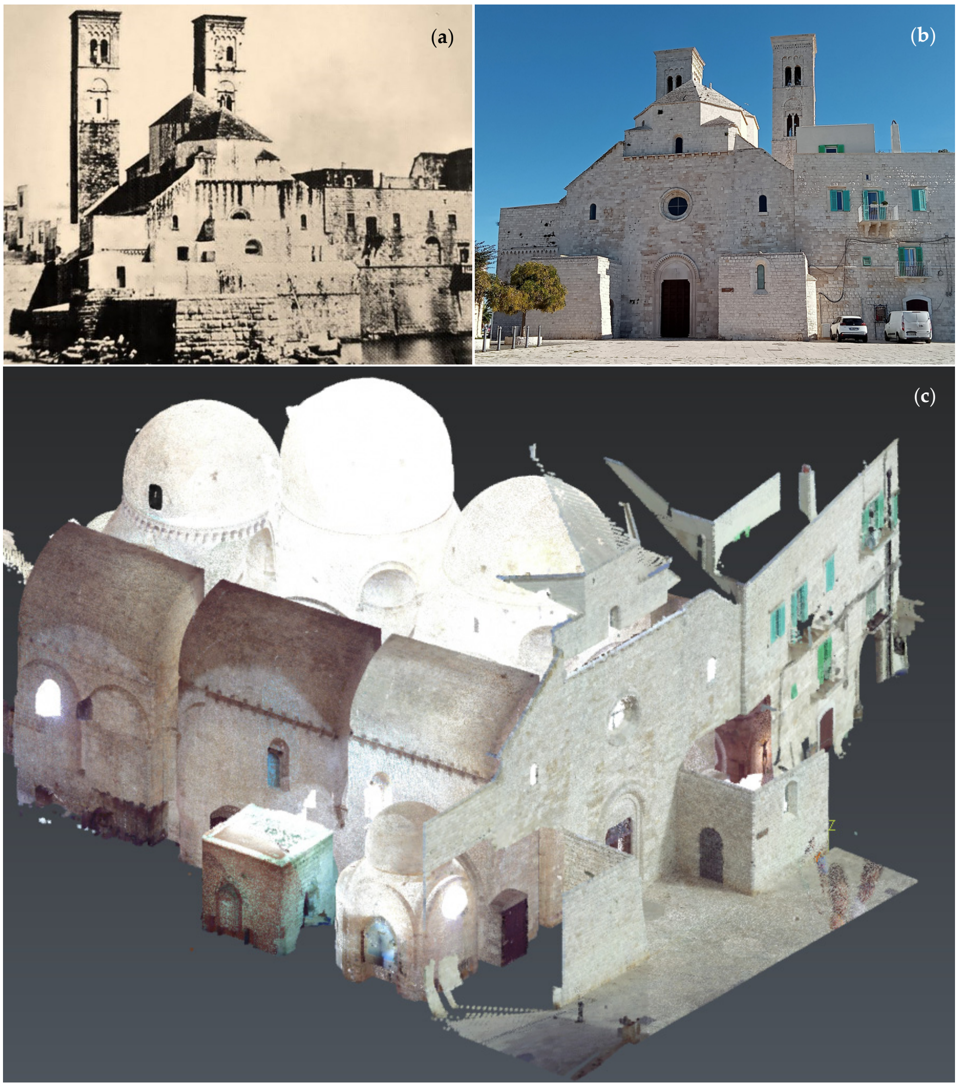


Figure 2. The Duomo of Molfetta: (**a**) an image from 1875, showing itself as a fortress facing the sea; (**b**) the view of the west facade (current main entrance); (**c**) the point cloud of the interior and exterior façade of access to the Duomo, both scanned.

3.2. Architectural Survey Process

The interior of the Duomo di Molfetta is scanned by a CAM2 FARO Focus 3D 120 scanner (TLS), with an accuracy of ±2 mm and a range of 0.6 m at 120 m, a registration speed of 976,000 points/second and a field of view of 305° in the vertical plane and 360° horizontally. The TLS survey was carried out by researchers from the Laboratory of Architectural and Urban Modelling (MAULab), Politecnico di Bari (Italy), and 56 positions were necessary for the complete scan of the interior of the Duomo, which includes the three main naves, the perimeter chapels, the presbytery, and the east-facing altar. The west-facing façade was the only part of the exterior scanned, as the aim of the study was mainly to capture the geometry and materiality of the interior of the Duomo, data that would later be used to analyze the deterioration in the structures still existing after the last restoration, highlighting the loss of material in some columns and vaults and cracks evident in the side walls of the envelope.

The scanning of the façade has served to provide metric data and scale the photogrammetry applied to the exterior of the building, properly coupling the point clouds of both processes and avoiding decompensation errors. Exterior capture is carried out by Digital Single Lens Reflex (DSLR) short-range photogrammetry. An 18-megapixel Canon E650D SLR camera (Canon Inc.,Tokyo, Japan) is used, with a CMOS (APS-C 14 × 22.3 mm^2) and optical image stabilizer. The photogrammetric process by Structure from Motion (SfM) is executed in the Agisoft Metashape software 1.8.2 Version 2022 (Figure 3a), allowing us to obtain portions of walls in textured 3D meshes that will then be incorporated into the HBIM project (Figure 3c). The meshes are previously optimized, reducing the number of triangles in Cyclone 3DR.

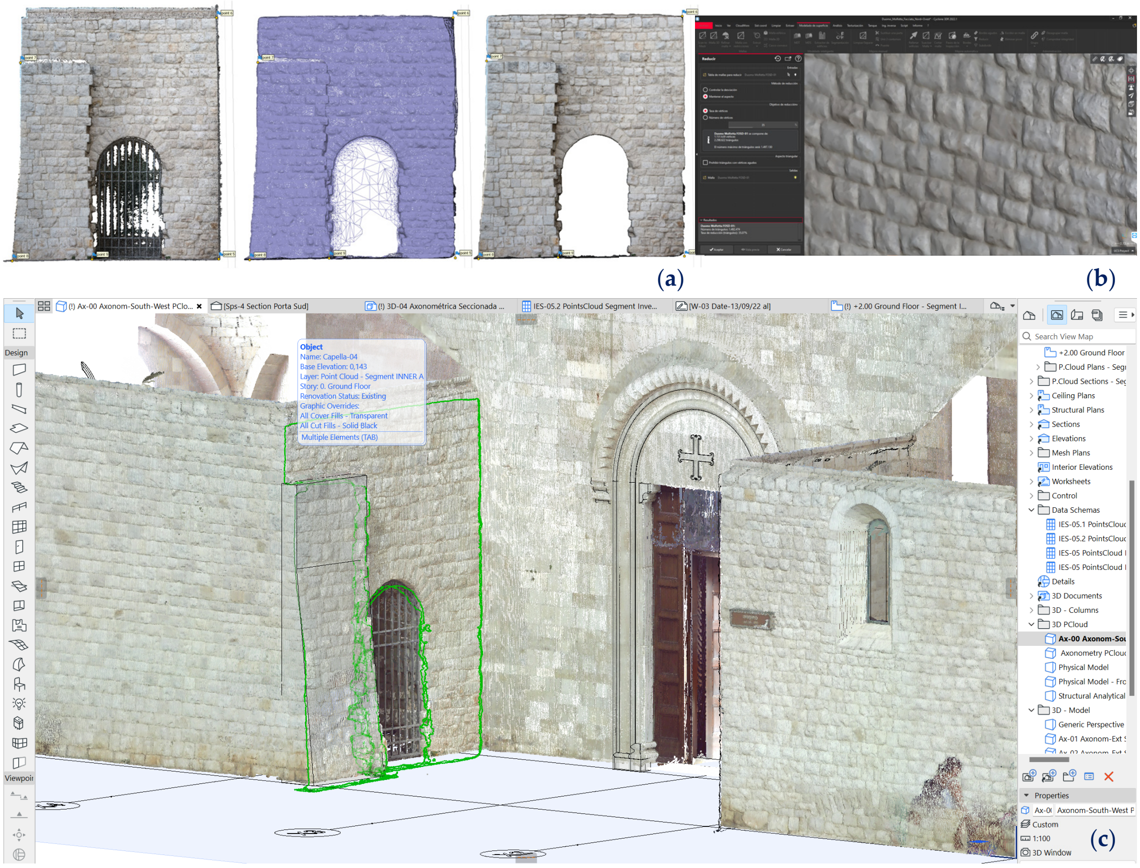


Figure 3. The meshing process of the wall with ashlars of the west façade of the Duomo di Molfetta: (**a**) the dense PC, 3D mesh, and textured mesh; (**b**) the reduction in triangles to 35% in Cyclone 3DR, prior to their insertion; (**c**) the object inserted in the HBIM project (Archicad v27).

3.3. Data Organization and Classification

For the global post-processing of the data, Leica Geosystems' Cyclone Register 360 is used to register the TLS scans and, subsequently, the Cyclone 3DR software for the coupling and management of the different point clouds (TLS and SfM), as well as for the semi-automatic semantic segmentation processes using analysis and classification algorithms. The workflow developed in Cyclone 3DR has been very effective for the limitation and effective visualization of the large point cloud, using 3D section boxes to focus on areas with complex geometries or that are difficult to access. This procedure facilitates the correct delimitation of the architectural geometries and the subsequent precise segmentation of decorative moldings of free forms, cornices, and architectural finials, with certain complexities at the intersection of the structural systems: the meeting of walls with pilasters, arches of discharges under the barrel vaults, and intersections of the hemispherical domes with the central vault. The process of semantic segmentation is exposed in Section 5. The results indicate the identification and classification of the structural entities of the Duomo. The HBIM project is based on Graphisoft®'s Archcad platform, where all the structured information from TLS and SfM processing is managed. Initially, all portions of the original file (supplied in rcp format) were previously managed from Recap Autodesk® to proceed with its appropriate orientation, georeferencing, and sectorization. The TLS global point cloud has not been reduced in post-processing so as not to lose important details in the decorative elements, mainly above, since the scanner parking lots were only placed on the pavements. The point cloud on the outside of the cathedral is inserted as a single whole. On the other hand, the interior is subdivided into four fractions before being incorporated into the HBIM project, and it is not necessary to reduce the number of points from post-processing (limit: 250 million points), before being converted into parametric objects. Next, all the datasets (e57 format) are exported to the Archicad BIM environment. It is important to underline the importance of always guaranteeing the best visualization and operability of the data in the HBIM project, so the datasets have been managed in different layers depending on their location or category once segmented (columns, walls, vaults, etc.), which has also allowed a better performance of the computer's graphics card. In a second phase, taking into account the semantic classification by architectural and structural categories, the overall point cloud of the interior will be segmented into characteristic subgroups. Data interoperability is one of the pillars of the BIM methodology workflow, so the information generated about the HBIM project has to be coordinated, structured, and classified so that all project stakeholders can transfer and share data. A BIM project must incorporate a classification system according to the requirements of the client or body responsible for its management. In the same way, one of the objectives of using classification in a Heritage BIM project is to provide the heritage sector with standardized terminology and semantics, which will allow the model to be structured with known bases to be shared by all collaborators. In addition, in order to follow the "open BIM" interoperability standards, the project must be structured in IFC format, which will contain an appropriate and consensual semantic classification. In this way, anyone who is outside the scope of being a BIM operator can visualize the model and be able to manage and identify independent elements.

Thinking about a system of structural elements of its own and, given the similarity of the classification with the work of Moyano et al. [45], a column-type element can be classified following an order based on its architectural composition, where all the parts are identified. Classification allows the model to be structured with standardized databases to define the attributes of each element or sub-elements. However, before applying segmentation to a construction element or system, it is important to properly structure an HBIM project, such as a cataloging process, in which semantic data are managed and included and organized according to a recognized classification.

3.4. Analysis and Control Process

To cover the conservation phases, specific properties are created for the identification and analysis of the deterioration detected in the building structures. It is in this phase that the potential of the BIM methodology for the efficient and interdisciplinary management of architectural heritage is highlighted, interacting directly with the semantically classified elements. Specifically, marking and labeling of the deterioration can be applied directly on the 3D model and specific schemes can be obtained to facilitate the recording of data in the analysis and control phases of the pathologies. The clarity and flexibility of the process in the risk assessment phase make conservation tasks in the HBIM project more efficient and precise.

4. Results

The results obtained from the applied methodology will be presented, a process that began with the planning of the TLS and photogrammetry surveys, going through the semantic segmentation of the relevant building typologies of the Duomo di Molfetta until reaching the semantically enriched parametric model.

4.1. Positioning System Configuration

In order to structure an HBIM project on the basis of optimal georeferencing, it is important to establish a common origin of the project in the different software used in the collaborative process, and thus interoperationalize data efficiently. In the case of the Duomo di Molfetta, the procedure applied has allowed the geolocation conditions of all the elements to coincide, facilitating interoperability and workflow between software. The precise position of the elements in the project was guaranteed at all times, covering new additions or subsequent substitutions in the process of semantic segmentation. Thus, the network of X,Y,Z axes in the BIM environment was adapted to the structural elements located in the point clouds, after they were inserted in the ArchiCAD HBIM project. The same X,Y,Z network system was transferred to the Cyclone 3DR environment, so that all the point cloud fragments originating from the segmentation process would go to the exact place with respect to the origin of the HBIM project (Figure 4).

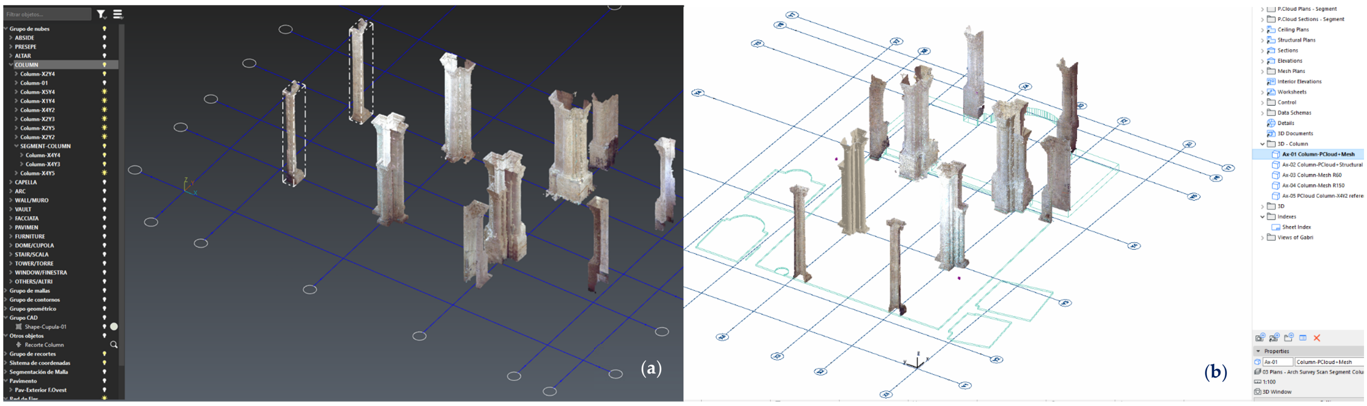


Figure 4. The segmented columns and pilasters of the TLS point cloud in the Cyclone 3DR environment (**a**), geopositioned in the same X,Y,Z network system of the Archicad HBIM project (**b**).

4.2. Sectorization of Point Clouds in Construction Elements and Systems

Once the point cloud is georeferenced by a package fit, and the workflow system has been verified to be correct, the appropriate segmentation by structural element is carried out. For the case study, the "Scan-to-mesh-BIM" workflow has been carried out through an implementation of the Cyclone 3DR software [40]. Due to the complexity of the geometric shapes of the architecture examined, the segmentation process should be classified as semi-automatic, since the current automatic classification algorithms are not very efficient for architectural heritage, which has resulted in an eminent assistance of the human operator.

The "box" tool has facilitated the sectorization of the point clouds, allowing the tasks of identifying points and cutting out delimiting surfaces until the characteristic geometry of the structural type is defined. In the case of some central pilasters, the level of development and knowledge (LOD-LOK) was increased, becoming segmented into smaller units: base, shaft, and capital (Figure 5). The semantic segmentation procedure has been extended to the entire interior of the Duomo di Molfetta, affecting the TLS point cloud (Figure 6a). These portions have then been inserted and classified into construction typologies in the HBIM project: arches, vaults, columns, walls, pilasters, and columns (Figure 6b).

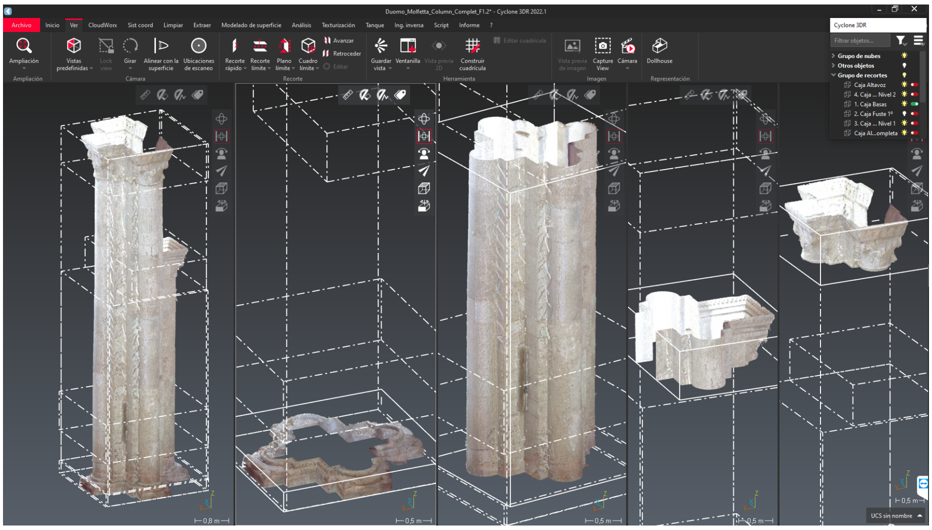


Figure 5. An image of the Column-X4Y3, and sectorization by box of the point cloud to differentiate bases, shafts, and capitals of the central pilasters of the Duomo di Molfetta.

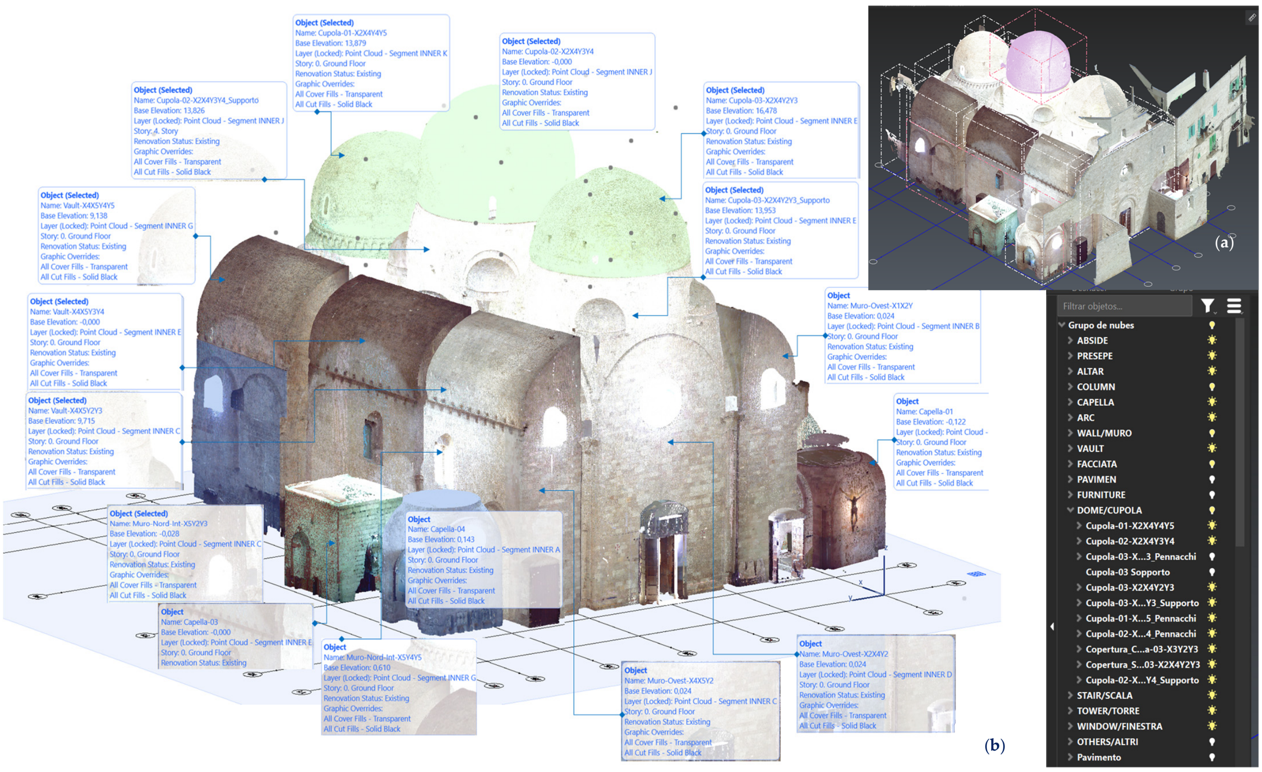


Figure 6. The semantic segmentation of the point cloud (TLS): (**a**) in the Cyclone 3DR environment, the typologies are delimited and separated with a box; (**b**) in the HBIM Project of the Duomo di Molfetta, groups of points are inserted and converted into parametric objects (Archicad 27 environment).

The process of semantic segmentation of the interior point cloud has resulted in an identification and classification of structural elements that acquire the identity of parametric objects, that is, belonging to the object library of the HBIM project (lcf file). Table 1 shows the inventory of 67 fractions, not including other elements that were also segmented, such as pavements, furniture, and auxiliary elements. The methodology followed provides an advance on previously developed works [38,46]. This has made it possible to create "interoperable" schemes for the inventory of fractions, which have been identified and classified according to the standardized bases incorporated in the project. The schemes will have relevant data for subsequent heritage conservation work, which will be described in Section 0.

Table 1. A scheme of the segmentation of the point clouds linked to the HBIM Project.

D Classification	Object Name	AC Class	Classification—SCFclass	Quan
PointCloud-Arc	Arc-X1X2Y4	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2X4Y3	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2X4Y4	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2X4Y5	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2Y2Y3	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2Y3Y4	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X2Y4Y5	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4X5Y3	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4X5Y3	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4X5Y4	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4Y2Y3	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4Y3Y4	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Arc-X4Y4Y5	Elemented Wall	FUN.EST.020.030.020 Arco	1
PointCloud-Arc	Muro-Arc-X1X2Y3	Solid Wall	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Column	Column-X1Y4	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X2Y2	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X2Y3	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X2Y4	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X2Y5	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X4Y2	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X4Y4	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X4Y5	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Column	Column-X5Y4	Pilaster	FUN.EST.020.010.010 Pilar	1
PointCloud-Cupola	Cupola-01-X2X4Y4Y5	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Cupola-01-X2X4Y4Y5_Fenestre	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Cupola-02-X2X4Y3Y4	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Cupola-02-X2X4Y3Y4_Supporto	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Cupola-03-X2X4Y2Y3	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Cupola-03-X2X4Y2Y3_Supporto	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Cupola	Pennacchi-Cop-01	Dome Roof	FUN.EST.020.030.030 Cúpula	1
PointCloud-Space	Altare	Internal Space	FUN.ARQ.040.010.090 Otro mobiliario fijo	1
PointCloud-Space	Capella-01	Internal Space	FUN.ARQ.020.020 Sistema de compart	1
PointCloud-Space	Capella-02	Internal Space	FUN.ARQ.020.020 Sistema de compart	1
PointCloud-Space	Capella-03	Internal Space	FUN.ARQ.020.020 Sistema de compart	1
PointCloud-Space	Capella-04	Internal Space	FUN.ARQ.020.020 Sistema de compart	1
PointCloud-Vault	Vault-X1X2Y2Y3	Barrel Roof	FUN.EST.020.030.010 Bóveda	1

Table 1. *Cont.*

D Classification	Object Name	AC Class	Classification—SCFclass	Quan
PointCloud-Vault	Vault-X1X2Y3Y4	Barrel Roof	FUN.EST.020.030.010 Bóveda	1
PointCloud-Vault	Vault-X1X2Y4Y5	Barrel Roof	FUN.EST.020.030.010 Bóveda	1
PointCloud-Vault	Vault-X4X5Y2Y3	Barrel Roof	FUN.EST.020.030.010 Bóveda	1
PointCloud-Vault	Vault-X4X5Y3Y4	Barrel Roof	FUN.EST.020.030.010 Bóveda	1
PointCloud-Vault	Vault-X4X5Y4Y5	Barrel Roof	FUN.EST.020.030.010 Bóveda	1
PointCloud-Wall	Abside	Internal Space	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Wall	Facciata-Ovest-Ppal-X1X6Y2	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Facciata-Ovest-Sup	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Facciata-Vicina-Destra	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	FOvest-Strov-Destra-X1X2Y1Y2	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	FOvest-Strov-Sinistra-X4X5Y1Y2	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro Ovest-Divisore Ingresso Ext	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro Ovest-Divisore Ingresso Int	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Est-X1X2Y5	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Est-X2X4Y5_Altar	Wall	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Wall	Muro-Est-X4X5Y5	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Nord-Int-X5Y2Y3	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Nord-Int-X5Y3Y4_0	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Nord-Int-X5Y3Y4_Capitel-X5Y3	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Nord-Int-X5Y4Y5	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Ovest-X1X2Y	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Ovest-X2X4Y2	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Ovest-X4X5Y2	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Sud-Int-X124Y3	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Sud-Int-X1Y3Y4_Capitel-X1Y3	Wall	FUN.EST.020.010.020 Ménsula estructural	1
PointCloud-Wall	Muro-Sud-Int-X1Y3Y4_Red	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Sud-Int-X1Y4Y5	Wall	FUN.ARQ.010.010.010.010 Fachada in situ	1
PointCloud-Wall	Muro-Vault-X1X2Y4	Wall	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Wall	Muro-Vault-X1X2Y5	Wall	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Wall	Muro-Vault-X4X5Y4	Wall	FUN.EST.020.010.030 Muro estructural	1
PointCloud-Win	Finestra-Altare	Window	FUN.ARQ.010.010.020.010 Ventana fach	1
			Total segments	**67**

4.3. Point Cloud Classification

To reduce the time spent on manual semantic labeling tasks, the process is increasingly being automated with the implementation of segmentation algorithms that segregate geometric shapes of architectural and constructive interest. Cyclone 3DR (C3DR) implements automatic classification models of construction systems, trained with current typologies, and which have been tested for the case study. According to the results, it has not been very effective in adequately detecting the architectural typologies of the Pugliese Romanesque. The algorithms for automatic detection and classification have only been effective when a sector was previously delimited with a box (Figure 6a). Therefore, manual pre-selection is still required to achieve valid results, calling the applied process semi-automatic. But other algorithms incorporated in C3DR classification tools have been used, such as the wall, floor, and ceiling arrest, which is very effective for discriminating sets of points that are located on the same flat surface. For the case studied, it has been applied to columns that have masonry with a high level of wear (Figure 7).

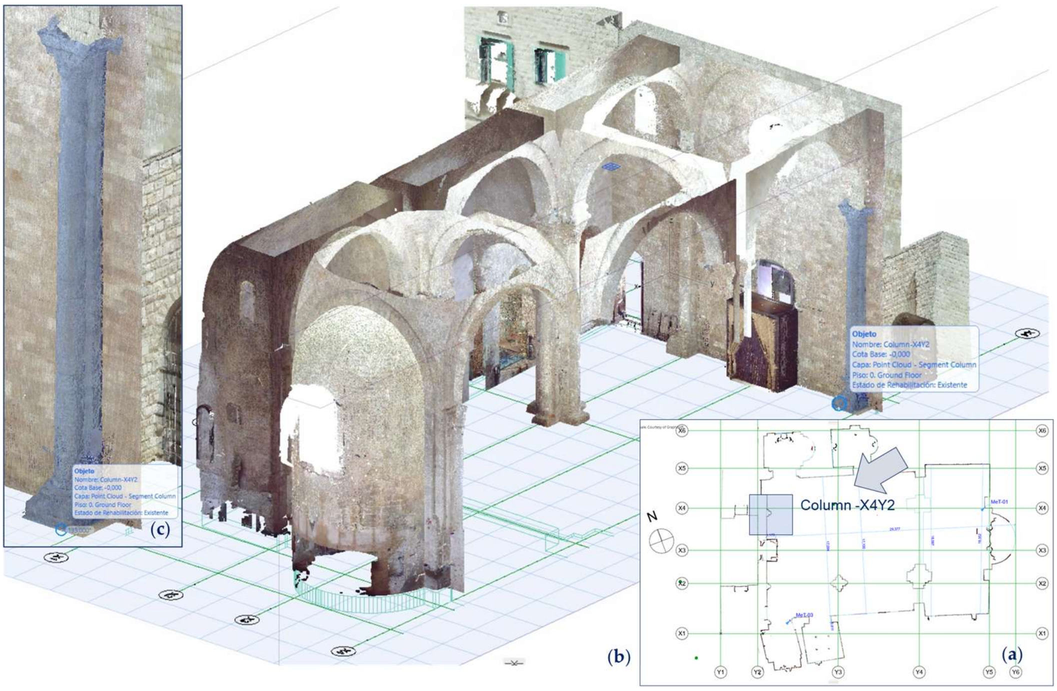


Figure 7. The point cloud of the Duomo of Molfetta in the HBIM project: (**a**) a plan with the position of Column-X4Y2; (**b**) a 3D section to the interior point cloud and selection of the Column-X4Y2 object, inserted in format e57; (**c**) the portion is converted into an Archicad library object (gsm/lcf file).

The process starts with a previous segmentation of points for the columns and pilasters of the Duomo. At the beginning, the appropriate tolerance parameters are chosen so that the selection is effective and logical: an angular tolerance for walls, another tolerance for floors and ceilings, and finally adjusting the "Local normal smoothing" for the classification process, which will vary between sharp or smoothed extremes. Due to the irregularities of the walls, floors, and ceilings the tolerance is brought to the maximum (10°) and the classification is activated for all the above types and others. The great irregularities in the walls, whether vertical or horizontal, are discarded within the group of planes such as wall (brown), floor (cyan), and roof (green). In the case of the column that rests on a pedestal, some upper points are classified as floor, although a large number incorporate them into the wall, in the case of those points identified as noise and that appear when the scanner's laser does not project well in the frontal plane due to the inclination of the horizontal plane. These elements are located at a higher height than the equipment, as is the case of the spine-pedestal, the capitals, the cornices or very high projecting strips. The tests carried out on the pilasters or columns have provided very significant data, since the finishes of the bases of columns and capitals are classified in others, due to the fact that their inclination is outside the range of the angular tolerance for walls or floors (10°). Due also to irregularities in the shaft of the column, many points have been classified as “Others” (gray color), including the carving or indentations of the capital decoration. Figure 8 shows the classification process of Column-X4Y2, identifying the points of the classes for walls (in brown), floors (in cyan), and ceilings (green).

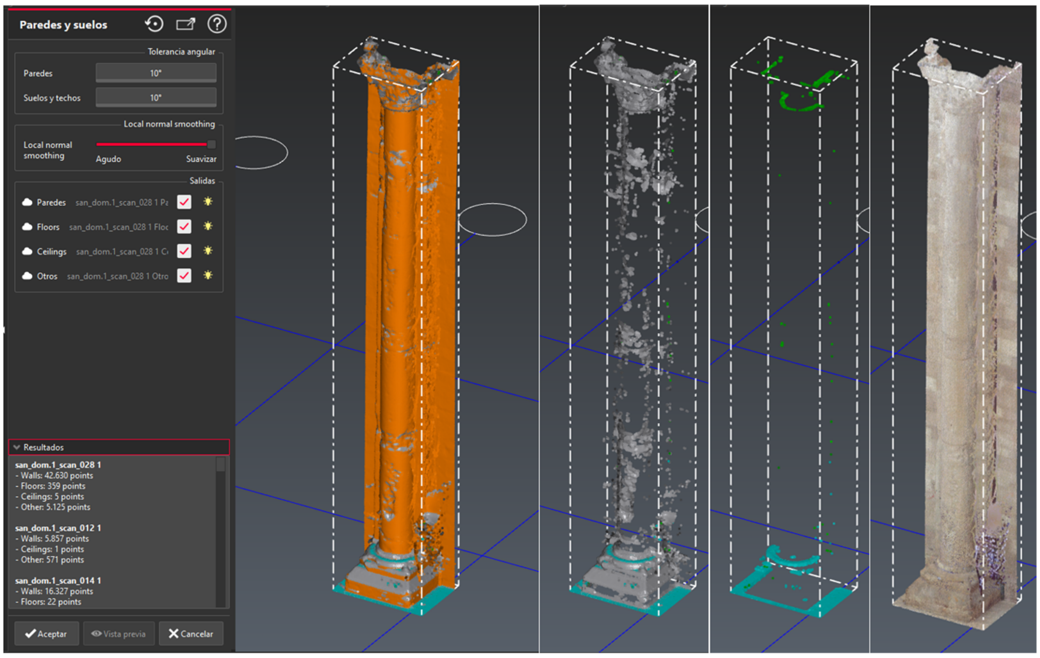


Figure 8. Column-X4Y2 classification: walls (brown); soils (cyan); roofs (green); others (in gray). The irregularities of the shaft are classified as other, as well as the carved decoration of the capital.

If the operator deems it necessary to fine-tune the segmentation process, the process is repeated because the system allows it, although it may be the case that a greater number of points are automatically filtered to be classified as “others”. Therefore, it is very important to apply the right tolerance. If the results are not very logical, the applicability of such algorithms to the classification sought should be ruled out. Finally, for the classification process of Column-X4Y2, one applies the following:

1. Segmentation of the column into three fundamental parts: base, shaft, and capital. The shaft contains many undulations due to wear and loss of material, so it is important for the algorithm to detect these parts (which differ from walls and floors) and apply only to deformations. In this way, the capital and the base would also be discarded as they are groups outside the wall and floor type.
2. Choice of tolerance parameters for classification: a minimum floor angle of 1° (minimum slope) and an angular tolerance for the walls (maximum angle with nadir-zenith line) with a high angle of 9° (1° min–10° max) as the column has a backward slump of 0.744° (Figure 10a).
3. The slider for normal local smoothing is applied. This slider allows you to increase or decrease the radius of the buffer in a cloud to account for a larger portion of the cloud. An intermediate of 0.013 m is chosen.

The final results provide the following quantification of points: 1,742,768—89% (paredes/walls) and 208,711—11% (other) of the total analyzed (1,951,479 points). Floors and ceilings are not included in the classification. As shown in Figure 9, a graphical analysis is performed in Cyclone 3DR filtering the points by classified typology. The points corresponding to the most pronounced deformations of the column (other) are evidenced with the gray color.

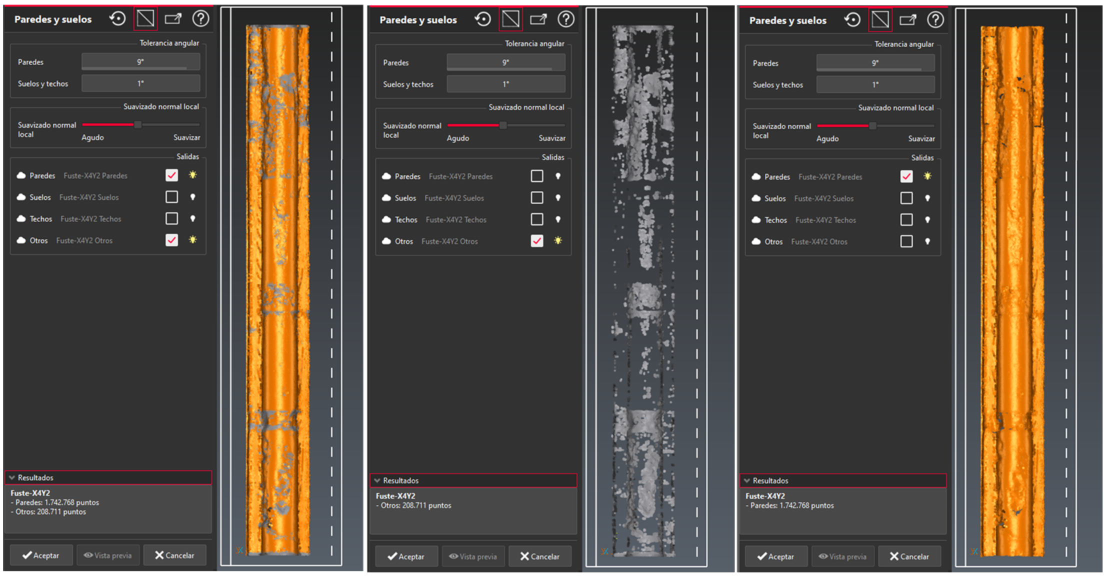


Figure 9. An image of Column-X4Y2 once it completes the last phase of points classification: 1,742,768—89% (paredes/walls, in brown) and 208,711—11% (other, in gray).

4.4. Analysis of Spinal Deformations

BIM platforms have the potential to compare complex forms of historical architecture with primitive shapes, which will determine the transformations in many cases. This is where the emphasis is placed in this research, since by exporting each of the segmented models as portions of the point cloud, the deformations can be compared on a millimeter scale. In the case of the column referenced to the X4Y2 axes, it has been possible to compare the collapse on both sides with the ideal plumb position. For the case study, a 3D model of the shaft element is developed, using the "pillar/column" tool of ArchiCAD and associating a constant theoretical profile throughout its height; the 3D element is finely adjusted to the collapses of the point cloud portion and also of the 3D mesh (derived from the segmented point cloud), since all of these are available within the HBIM project. The result of the comparative study shows a collapse of the column of $-0.744°$ in the direction of the west façade (Figure 10a), and considerable deviations in -X, delimited in red in the horizontal section to +7.36 m (Figure 10b).

In turn, another comparison is made in the Cyclone 3DR (C3DR) software, taking advantage of the analysis of geometries when comparing models between types. The following are the four available options: (i) between two 3D meshes, derived from two different processes and with different resulting polygons; (ii) point cloud with 3D mesh; (iii) 3D mesh with BIM; and (iv) 3D BIM geometry with point cloud. The last option was chosen because it is the most suitable to be able to extract accurate deviation reports from each of the planes. Based on this, the BIM model of the column is exported from ArchiCAD in IFC format and then incorporated into C3DR. Also, the point portions of the segmented columns are converted to C3DR 3D mesh. In the case of Column-X4Y2, there are three 3D meshes that correspond to the base, shaft, and capital.

It was finally decided on option iv) of C3DR to buy the theoretical 3D object adapted to the point cloud with the 3D mesh, based on a "best fit" by choosing the homologous points in both geometries. It must be said that, in this case, the common coordinate system is georeferenced to the same origin of the project, so when exporting the IFC object to the Cyclone environment, the two models are adjusted. From now on, the deformations can be analyzed, using different cross-sections (every fifteen centimeters in our case) along the entire shaft. Figure 11 shows the points taken at the base and at the crown of the shaft, which have served as a reference to adjust the theoretical and real geometries, and thus obtain an accurate report of millimetric deviations of the shaft.

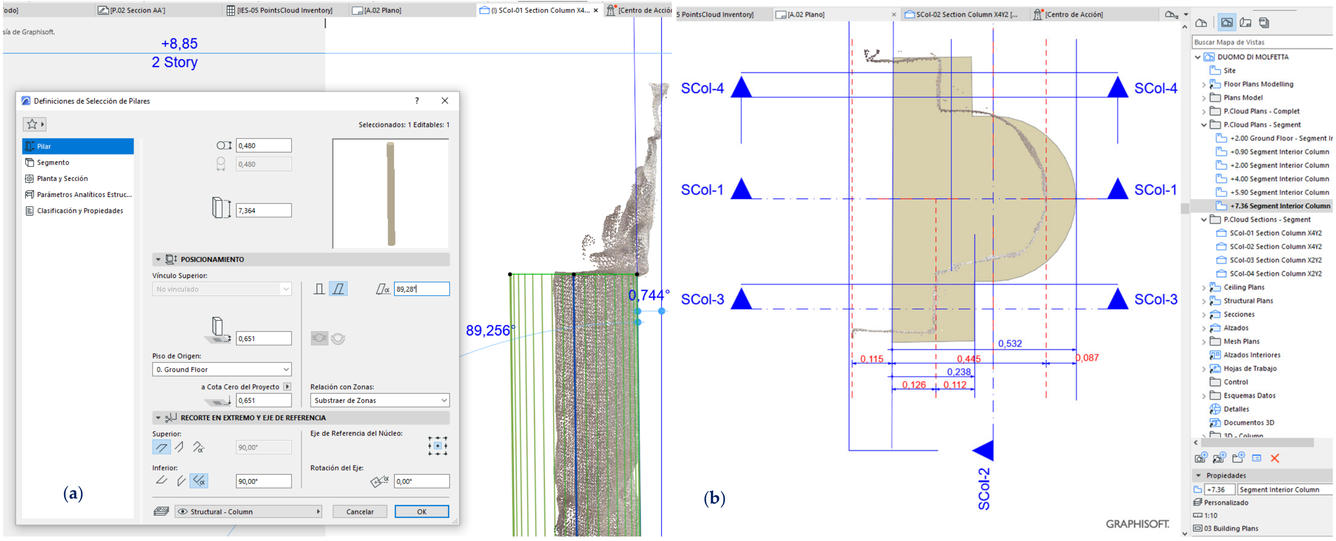


Figure 10. A column modeled in Archicad and compared with the mesh imported from Cyclone (IFC format). It is analyzed and dimensioned to extract the collapses suffered by the column: (**a**)—0.744° in the direction of the west façade; (**b**) the horizontal section at +7.36 m with the deviation −X (red color).

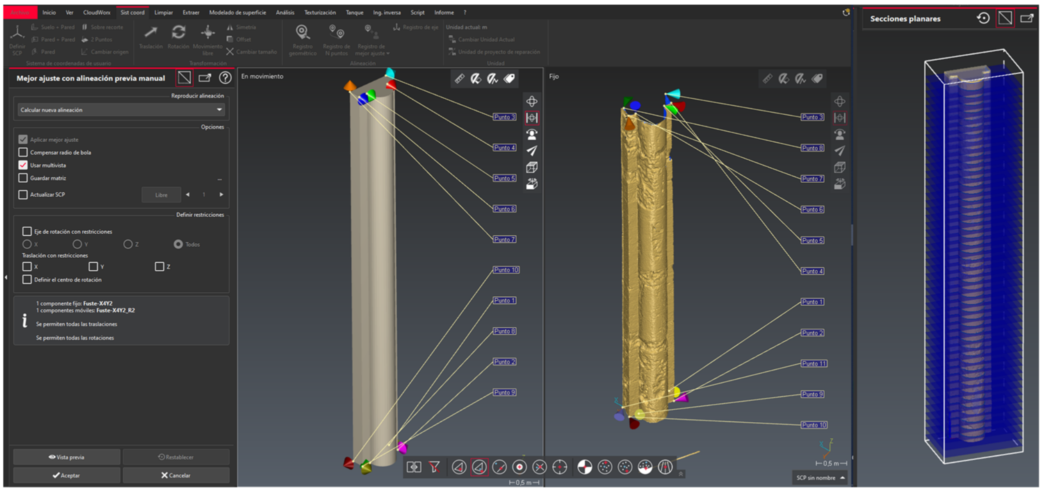


Figure 11. The theoretical model exported in IFC format and the mesh generated from the point cloud; the section plans were made to the shaft every 15 cm (Leica Cyclone 3DR).

In previous works, Moyano et al., 2021 [16] evaluated the quality of the 3D model compared to TLS data, employing Cloud Compare v2 software and complemented with specific algorithms in the Dynamo environment for a porticoed structure. Now, in the new case, implementing the C3DR environment provides a great advantage of operability in the workflow between the parametric 3D model (HBIM project), using the standard IFC format, and the environment of a specific point cloud analysis and reverse engineering software.

Once the parametric shaft model has been reverted to the point cloud processing environment, C3DR's "mesh vs BIM comparison" is used to obtain deviation results. A graph of deviations from the reference plane of the theoretical model is generated, showing regions in color that vary from red (+) to blue (−) and that represent the positive (protruding) and negative (perforation) deformations, respectively, as can be seen in Figure 12. The color graph shows up to a deviation of 0.06 m (maximum distance), giving maximum deviation and percentage values of +0.038 m (0.1%) and −0.053 m (0.2%).

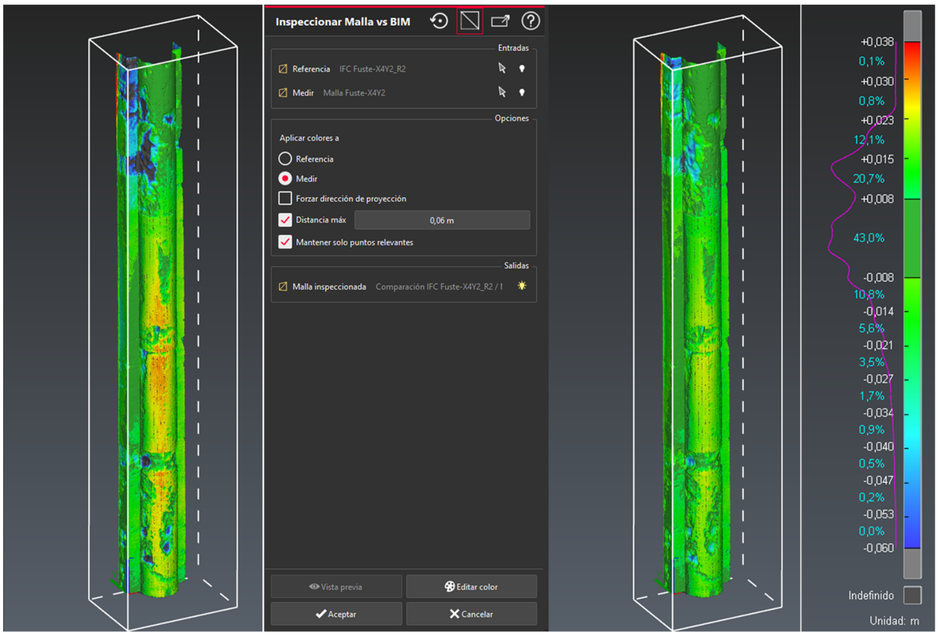


Figure 12. The results of the comparison between the theoretical model and the real model with the color result graph (Leica Cyclone 3DR).

The HBIM project must constitute a nucleus containing all the information generated in the processes. For this reason, the data related to the external analysis and control work have been incorporated, which, in the case of the previous column exposed, have corresponded to the results of the impairment report, and are derived from the comparison between the theoretical model and the real model. Figure 13 shows some of the most significant sections of the report after comparing the point clouds with the theoretical surface of Column-X4Y2 shaft. The data of the deviations (average, minimum, maximum) in each horizontal section given to the shaft are collected in Table 2. To analyze all sections of the Report, after comparing the point clouds with the theoretical surface of the X4Y2-column axis, please refer to the Supplementary Materials.

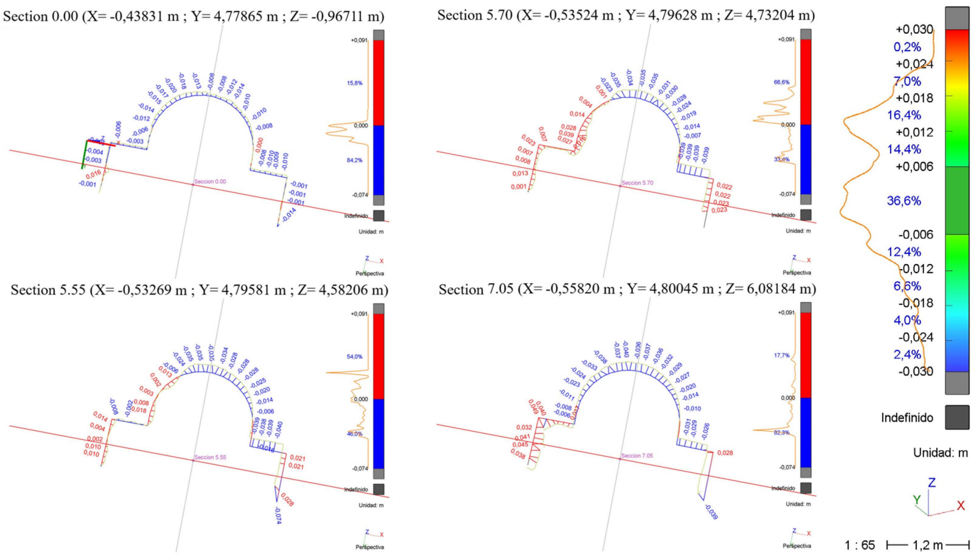


Figure 13. The sections taken from the report to compare the point clouds with the theoretical surface of Column- X4Y2 shaft (Cyclone 3DR).

Table 2. The data of the deviations (average, minimum, maximum) in each horizontal section given to the shaft of Column-X4Y2.

Section	Desv. Pr. (m)	D. mín. (m)	D. máx. (m)
Section 0.00	−0.00653	−0.01994	0.01553
Section 0.15	−0.00915	−0.02205	0.00932
Section 0.30	−0.00600	−0.02157	0.04881
Section 0.45	−0.00450	−0.02339	0.03249
Section 0.60	−0.00589	−0.02378	0.03059
Section 0.75	−0.00713	−0.02487	0.01258
Section 0.90	−0.00825	−0.02659	0.01728
Section 1.05	−0.01109	−0.02765	0.00703
Section 1.20	−0.00924	−0.05111	0.01171
Section 1.35	−0.00987	−0.03155	0.01161
Section 1.50	−0.01105	−0.04798	0.02569
Section 1.65	0.00469	−0.04241	0.03671
Section 1.80	−0.00850	−0.03267	0.01419
Section 1.95	−0.01257	−0.03231	0.00752
Section 2.10	−0.01141	−0.03297	0.00917
Section 2.25	−0.01247	−0.03458	0.00816
Section 2.40	−0.01242	−0.03558	0.00757
Section 2.55	−0.01405	−0.03712	0.00942
Section 2.70	−0.01369	−0.03796	0.01120
Section 2.85	−0.01169	−0.03915	0.01525
Section 3.00	−0.01383	−0.04137	0.01250
Section 3.15	−0.00514	−0.03706	0.02599
Section 3.30	−0.00977	−0.03961	0.01360
Section 3.45	−0.01252	−0.03274	0.01491
Section 3.60	−0.01769	−0.04245	0.01260
Section 3.75	−0.01568	−0.04240	0.01317
Section 3.90	−0.01411	−0.04274	0.01360
Section 4.05	−0.01457	−0.04200	0.01447
Section 4.20	−0.01442	−0.04138	0.01375
Section 4.35	−0.01391	−0.04030	0.01342
Section 4.50	−0.01459	−0.04045	0.01619
Section 4.65	−0.01557	−0.04142	0.01712
Section 4.80	−0.01455	−0.04007	0.01963
Section 4.95	−0.02316	−0.04074	0.01991
Section 5.10	−0.00972	−0.03993	0.02097
Section 5.25	−0.01144	−0.03948	0.02201
Section 5.40	−0.00598	−0.04435	0.09054
Section 5.55	−0.00173	−0.07380	0.02808
Section 5.70	0.00142	−0.03929	0.03912
Section 5.85	−0.00186	−0.05727	0.05121
Section 6.00	0.00190	−0.03662	0.03283
Section 6.15	−0.00675	−0.03715	0.02814
Section 6.30	−0.00486	−0.03500	0.03209
Section 6.45	−0.00518	−0.03766	0.03320
Section 6.60	0.00161	−0.03850	0.04433
Section 6.75	−0.01300	−0.03837	0.03851
Section 6.90	−0.00952	−0.03936	0.03022
Section 7.05	−0.01761	−0.04033	0.04967

4.5. Parametric Modeling in HBIM Project

The parametric modeling of the historic building is carried out in parallel with the process of analyzing the deformations of the column. The HBIM project is supported from the beginning by the TLS and photogrammetry point clouds, initially based on the global clouds (inside and outside) and later by the fragmentation into characteristic elements of the architecture analyzed. The objective is to obtain a 3D model of essential parametric typology without exerting greater efforts in the representation of architectural decorations that have little transcendence in the structural aspect. It would mean an approximation to the Level of Detail (LOD) 200 in its development since the project contains a semantic segmentation of all the structural and architectural systems provided by the point clouds. To do this, the basic tools of Archicad are used to model the general construction elements of the building, such as walls, floors, ceilings, roofs, and openings, setting aside the typologies that incorporated irregular and complex surfaces to be later transformed into mesh surfaces, such as columns, pilasters, walls, vaults, and domes.

The detailed modeling process of the architectural elements is mainly satisfied with the Cyclone 3DR reverse engineering software for their subsequent precise insertion into the HBIM project. The photogrammetric process by SFM is developed in Metashape, although it only affects certain panels of exterior walls that were captured by DLSR. As for the types of doors and windows, the flexibility of Archicad Graphisoft's library of architectural objects, based on GDL programming, satisfactorily saves the parameterization and graphic representation of the characteristic geometries of the Romanesque of Puglia. Although not a priority, some of the decorative elements present in cornices, moldings, and friezes are solved with the efficiency and flexibility of the "complex profile" and "morph" tools. Figure 14a shows the inner point cloud reference (TLS) to the Duomo parametric model in the HBIM project.

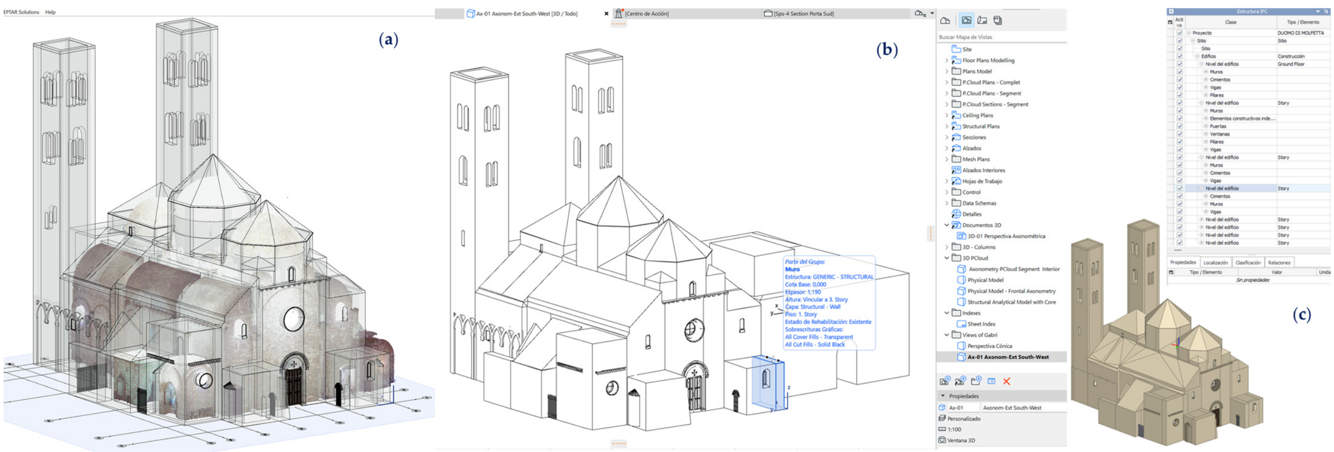


Figure 14. The parametric model of the Duomo di Molfetta: (**a**) referenced to the TLS point cloud (Archicad); (**b**) the simplified model of the HBIM project; (**c**) the exported IFC model, with the properties of the elements (BIMvision).

It is important to note that all the fractions of the point cloud (segmented groups converted into library elements—gsm/lcf file format) have gone through a process of identification and classification by functions and construction typologies. The resulting object is very valid because it shows the delimited geometry and the real texture, in the form of points, ready to be enriched by the semantic properties of an architectural type, structures, and others typical of the conservation process. The quality of the representation will depend on the resolution taken and the conditions of the environment at the time of scanning: position of the equipment, difficulty in capturing top, back and corner areas, and the high intensity of the light or contrast in the place. In the case study, the quality has met the needs of auscultation and analysis.

Finally, the complete HBIM semantic model, fully identified and classified (Figure 14b), was exported with the "Exact Geometry Export" (Archicad) option and therefore interoperable in IFC format. Figure 14c shows the model with the IFC data structure, using the BIMvision® (https://bimvision.eu/about/ (accessed on 25 November 2024)) viewer to explore the properties of all its elements.

4.6. Heritage Conservation Work

The conservation work of the Duomo di Molfetta is carried out on the basis of an exchange of information based on a collaborative HBIM project [46] where specialists work in real time to implement the procedures. The management of all the data provided by the TLS point cloud covers an important phase of the process, contributing to the accuracy and similarity of the morphological characteristics of the object. The project for the exchange of information between collaborators was born with the applicability of Teamwork on the BIM platform Archicad. From this operation, a management of listed movable assets (sacristy paintings) is developed, also constituting a very valuable support for the architectural and construction systems of the historic building. This methodological process was reinforced with the interoperability of semantic data exposed in [47], proposing a method of defining ontologies in an HBIM environment and that is capable of managing and sharing data derived from the Conservation Process following the Preventive and Planned Conservation approach. Figure 15 shows a graph with the complete process, reinforced with the interoperability of the semantic data, following the phases of Segmentation and Identification, Ontology—Semantic classification, Identification of Deterioration, Marking and Labeling of Deterioration, and Risk Assessment.

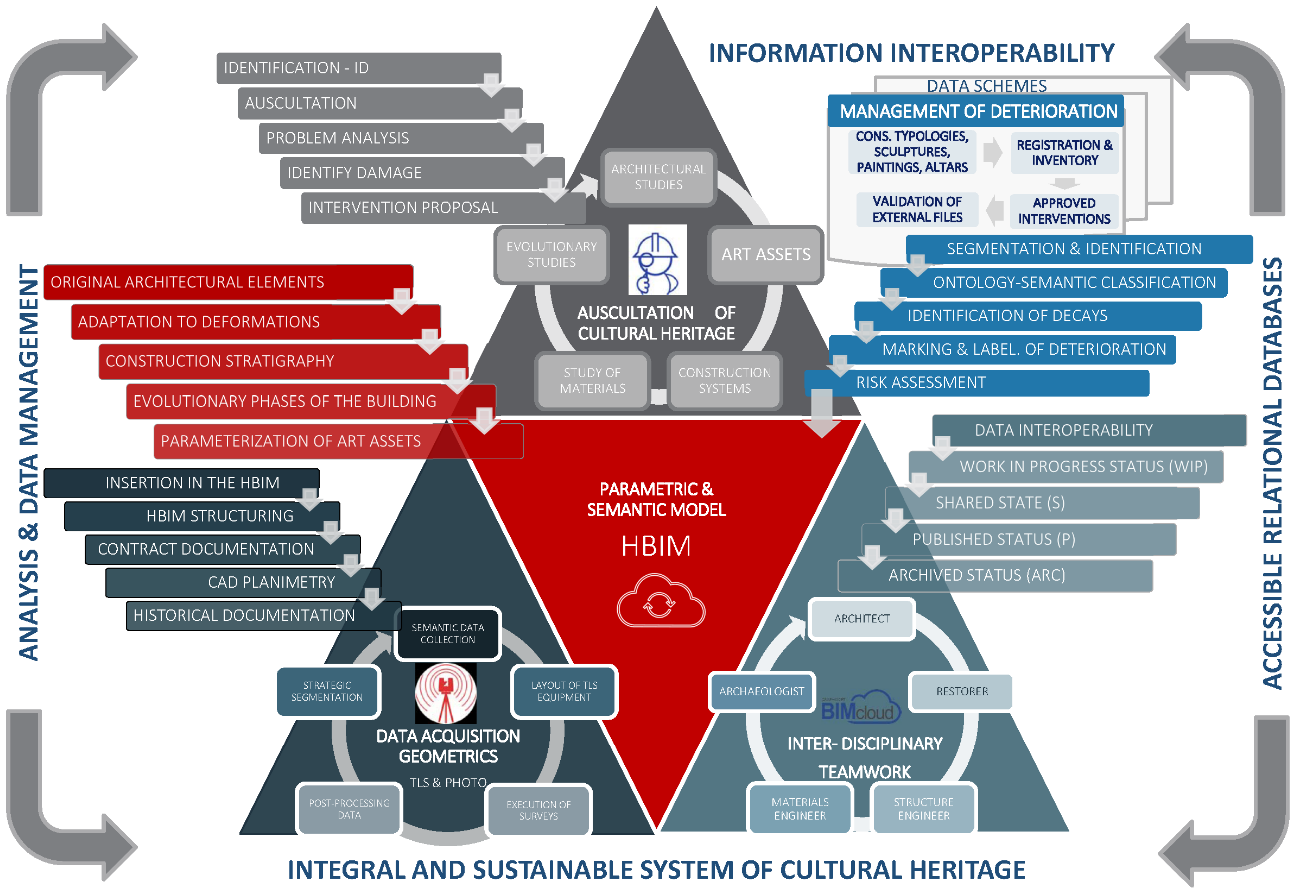


Figure 15. The methodological process for the conservation of cultural heritage, reinforced with the interoperability of ontological data for impairment management.

In this section, we expose the entire workflow developed for conservation, managed from the HBIM project itself, focusing mainly on the management of the deterioration of the historic building (Figure 16).

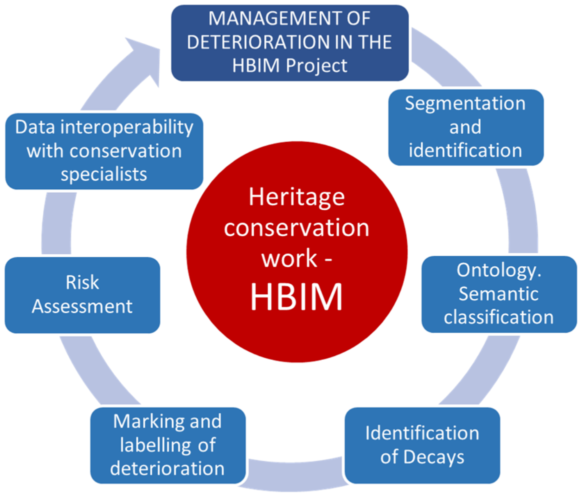


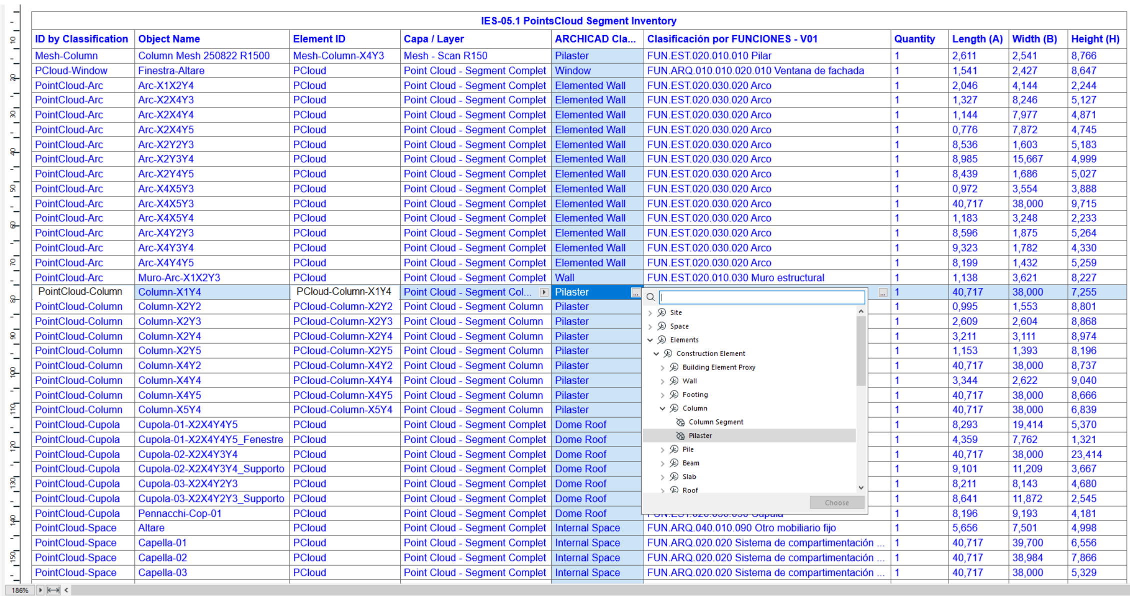
Figure 16. The workflow diagram in the HBIM project environment for the Preventive Conservation and deterioration management phase.

4.6.1. Management of Deterioration in HBIM Project

For the management of conservation processes in the BIM environment, specific properties have been created for the identification and analysis of the degradation (decay) detected in the building structures. In the case of the Duomo di Molfetta, we have focused on the wear and fragmentation located in the structural elements such as columns and pilasters. It is intended that the methodology applied will reinforce the interoperability of the HBIM project data with conservation and restoration specialists. The properties have been grouped by categories: Historical Information, Decay, Diagnostic Monitoring, Risk Assessment, Attachments Manager, and Cost Conservation. Once the parametric entities have been identified and classified, to help in the auscultation processes of the "Decay", the HBIM project has properties that are common in control and inspection activities: Bistering, Esfoliation, Lack, Detachment, Crack, among other things. In this way, the restoration technician can select the given 3D element and have in its editable definitions ("Classification and Properties" section) the "Tipe Decay" options, to be marked and applied to in the HBIM project. Property management can be performed in the selected element's own definition window or in the interactive schema. Subsequently, specific schemes or data tables have been formed that incorporate appropriate items for the identification of the elements, as well as particular properties of a conservation process (intervention, control, or maintenance). The specialist technician involved can now make a multi-selection among the options available in the scheme. The listed parametric elements have links to be displayed in plan and 3D views.

4.6.2. Segmentation and Identification

In BIM models, classifying involves relating a BIM entity to the semantic typology or level of a classification system, assigning it its code and description. When an element is assigned different codes, a multi-classified element is obtained. For the case under study, the Duomo of Molfetta, the global point cloud of the interior has been introduced by fragments, segmented by their semantics, arranging the same elements in the HBIM project with the possibility of giving them the appropriate parametrics according to their constructive characteristics, structures, history, and other properties related to the conservation and restoration processes (Figure 17).



IES-05.1 PointsCloud Segment Inventory									
ID by Classification	Object Name	Element ID	Capa / Layer	ARCHICAD Cla...	Clasificación por FUNCIONES - V01	Quantity	Length (A)	Width (B)	Height (H)
Mesh-Column	Column Mesh 250822 R1500	Mesh-Column-X4Y3	Mesh - Scan R150	Pilaster	FUN.EST.020.010.010 Pilar	1	2,611	2,541	8,766
PCloud-Window	Finestra-Altare	PCloud	Point Cloud - Segment Complet	Window	FUN.ARQ.010.010.020.010 Ventana de fachada	1	1,541	2,427	8,647
PointCloud-Arc	Arc-X1X2Y4	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	2,046	4,144	2,244
PointCloud-Arc	Arc-X2X4Y3	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	1,327	8,246	5,127
PointCloud-Arc	Arc-X2X4Y4	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	1,144	7,977	4,871
PointCloud-Arc	Arc-X2X4Y5	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	0,776	7,872	4,745
PointCloud-Arc	Arc-X2Y2Y3	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	8,536	1,603	5,183
PointCloud-Arc	Arc-X2Y3Y4	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	8,985	15,667	4,999
PointCloud-Arc	Arc-X2Y4Y5	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	8,439	1,686	5,027
PointCloud-Arc	Arc-X4X5Y3	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	0,972	3,554	3,888
PointCloud-Arc	Arc-X4X5Y3	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	40,717	38,000	9,715
PointCloud-Arc	Arc-X4X5Y4	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	1,183	3,248	2,233
PointCloud-Arc	Arc-X4Y2Y3	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	8,596	1,875	5,264
PointCloud-Arc	Arc-X4Y3Y4	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	9,323	1,782	4,330
PointCloud-Arc	Arc-X4Y4Y5	PCloud	Point Cloud - Segment Complet	Elemented Wall	FUN.EST.020.030.020 Arco	1	8,199	1,432	5,259
PointCloud-Arc	Muro-Arc-X1X2Y3	PCloud	Point Cloud - Segment Complet	Wall	FUN.EST.020.010.030 Muro estructural	1	1,138	3,621	8,227
PointCloud-Column	Column-X1Y4	PCloud-Column-X1Y4	Point Cloud - Segment Col...	Pilaster		1	40,717	38,000	7,255
PointCloud-Column	Column-X2Y2	PCloud-Column-X2Y2	Point Cloud - Segment Column	Pilaster		1	0,995	1,553	8,801
PointCloud-Column	Column-X2Y3	PCloud-Column-X2Y3	Point Cloud - Segment Column	Pilaster		1	2,609	2,604	8,868
PointCloud-Column	Column-X2Y4	PCloud-Column-X2Y4	Point Cloud - Segment Column	Pilaster		1	3,211	3,111	8,974
PointCloud-Column	Column-X2Y5	PCloud-Column-X2Y5	Point Cloud - Segment Column	Pilaster		1	1,153	1,393	8,196
PointCloud-Column	Column-X4Y2	PCloud-Column-X4Y2	Point Cloud - Segment Column	Pilaster		1	40,717	38,000	8,737
PointCloud-Column	Column-X4Y4	PCloud-Column-X4Y4	Point Cloud - Segment Column	Pilaster		1	3,344	2,622	9,040
PointCloud-Column	Column-X4Y5	PCloud-Column-X4Y5	Point Cloud - Segment Column	Pilaster		1	40,717	38,000	8,666
PointCloud-Column	Column-X5Y4	PCloud-Column-X5Y4	Point Cloud - Segment Column	Pilaster		1	40,717	38,000	6,839
PointCloud-Cupola	Cupola-01-X2X4Y4Y5	PCloud	Point Cloud - Segment Complet	Dome Roof		1	8,293	19,414	5,370
PointCloud-Cupola	Cupola-01-X2X4Y4Y5_Fenestre	PCloud	Point Cloud - Segment Complet	Dome Roof		1	4,359	7,762	1,321
PointCloud-Cupola	Cupola-02-X2X4Y3Y4	PCloud	Point Cloud - Segment Complet	Dome Roof		1	40,717	38,000	23,414
PointCloud-Cupola	Cupola-02-X2X4Y3Y4_Supporto	PCloud	Point Cloud - Segment Complet	Dome Roof		1	9,101	11,209	3,667
PointCloud-Cupola	Cupola-03-X2X4Y2Y3	PCloud	Point Cloud - Segment Complet	Dome Roof		1	8,211	8,143	4,680
PointCloud-Cupola	Cupola-03-X2X4Y2Y3_Supporto	PCloud	Point Cloud - Segment Complet	Dome Roof		1	8,641	11,872	2,545
PointCloud-Cupola	Pennacchi-Cop-01	PCloud	Point Cloud - Segment Complet	Dome Roof	[illegible]	1	8,196	9,193	4,181
PointCloud-Space	Altare	PCloud	Point Cloud - Segment Complet	Internal Space	FUN.ARQ.040.010.090 Otro mobiliario fijo	1	5,656	7,501	4,998
PointCloud-Space	Capella-01	PCloud	Point Cloud - Segment Complet	Internal Space	FUN.ARQ.020.020 Sistema de compartimentación ...	1	40,717	39,700	6,556
PointCloud-Space	Capella-02	PCloud	Point Cloud - Segment Complet	Internal Space	FUN.ARQ.020.020 Sistema de compartimentación ...	1	40,717	38,984	7,866
PointCloud-Space	Capella-03	PCloud	Point Cloud - Segment Complet	Internal Space	FUN.ARQ.020.020 Sistema de compartimentación ...	1	40,717	38,000	5,329

Figure 17. The marking and selection of the parameters associated with the filtered elements from the same scheme of the HBIM project: the PointCloud-Column portion is classified as a pilaster. (image captured from the Archicad interface).

4.6.3. Ontology Semantic Classification

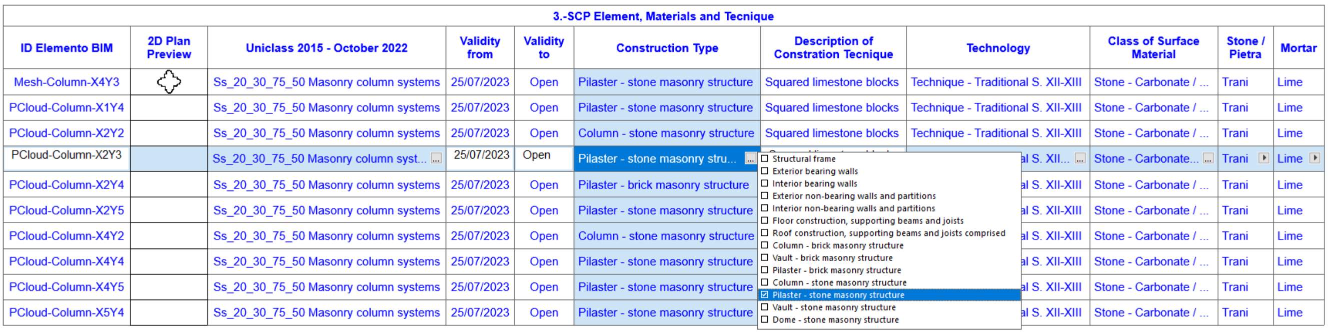
For conservation work, the Teamwork HBIM specialist must have all the information on the auscultation, control, and diagnosis work, having at their disposal the historical references and conservation data of the property. For them, the HBIM project relies on schemas that incorporate the items of the property groups.

The point cloud portions of the Duomo have been structured into essential building sub-units. For its classification, the most advanced systems have been used, mainly based on the new classification SCFClass [48] and the Uniclass [49], classifying the structural system and coatings according to their materiality. The new classification systems (SCs), such as the SCFClass Classification System (Spain), allow several classes to be applied within the same SC table: an element can thus be multi-classified because it contains different variants of materials according to the MATERIALS table (ceramic brick masonry, ashlar masonry, lime mortar, natural pigments) and by various concepts of "activities" of the work (preparation of the brick or ashlar masonry, lime plaster, fresco painting). Although it must be recognized that we face certain difficulties here, when seeking the best adaptation of the database, made up of contemporary and recognized construction systems, to previous techniques that are not currently common or because materials that are not currently commercialized are used.

The diagram shown in Figure 18 is an example of the process where the portions corresponding to the columns of the Duomo di Molfetta have been filtered. The technician directly interacts for the assignment of the properties (Construction Type, Description of Technique, Technology, Class of Material, Mortar), having for each one a series of pre-established options for its proper marking.

4.6.4. Identification of Decays

An important task in the control and diagnosis work is the appropriate auscultation, in order to classify the deterioration detected in the structure of the building and those existing pathologies in the coatings or finishes of floors, walls, columns, pilasters, arches, vaults, and ceilings. In the case study, all the elements are bare of cladding, with the stone masonry of the Romanesque architecture characteristic of the Puglia region (Italy) being visible. This allows for better detection and measurement of detachments, fissures and other types of deterioration in wall masonry.



3.-SCP Element, Materials and Tecnique										
ID Elemento BIM	2D Plan Preview	Uniclass 2015 - October 2022	Validity from	Validity to	Construction Type	Description of Constration Tecnique	Technology	Class of Surface Material	Stone / Pietra	Mortar
Mesh-Column-X4Y3		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	Squared limestone blocks	Technique - Traditional S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X1Y4		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	Squared limestone blocks	Technique - Traditional S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X2Y2		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Column - stone masonry structure	Squared limestone blocks	Technique - Traditional S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X2Y3		Ss_20_30_75_50 Masonry column syst...	25/07/2023	Open	Pilaster - stone masonry stru...	[illegible]	...al S. XII...	Stone - Carbonate...	Trani	Lime
PCloud-Column-X2Y4		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - brick masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X2Y5		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X4Y2		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Column - stone masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X4Y4		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X4Y5		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime
PCloud-Column-X5Y4		Ss_20_30_75_50 Masonry column systems	25/07/2023	Open	Pilaster - stone masonry structure	[illegible]	...al S. XII-XIII	Stone - Carbonate / ...	Trani	Lime

Figure 18. The schema of classified PCloud-Column elements, incorporating the properties Construction Type, Description of Technique, Technology, Class of Material, and Mortar. It interacts in the HBIM project by allowing a multiselection of items by properties. (image captured from the Archicad).

Based on the same SCFClass.V2 classification system, the Phase classification has also been used, specifically the *FAS.OCO Construction project*. However, as there is no specific category for conservation/preservation projects, the new phase *FAS.PCO.050 Execution of the Preservation Project* has been created. Thus, the Decays scheme of the Duomo Columns shows all the columns/pilasters classified by their system (*Column/Pilaster* - SCFClass (https://www.railwayinnovationhub.com/bim/ (accessed on 25 November 2024)); *Mansory column systems* –Uniclass) and for its *Execution of the Preservation Project* phase. In turn, the new *FAS.PCO.050.01 Mapping of degradation* class has also been applied, which has allowed mapping the localized Decays, which in the case of Column-X4Y3 have been of the type: Lack and Crack (Figure 19).

4.6.5. Marking and Labeling of Deterioration

Visual representation tools, whether of the 2D/3D polyline type or surface with pattern and color, are very useful both in the phase of graphic marking and in identification and classification, as they also act as container elements of semantic information. Once these assets are used, the graphics created in the HBIM environment are associated with implicit properties collected in the Conservation Process database.

As mentioned above, a multiple selection of localized deteriorations (Lack and Crack) has been applied in Column-X4Y3. As a reinforcement, an adequate, or better location in the HBIM project, they have also been graphically marked with a contour (3D polyline of the Morph tool) and a labeling associated with the "Note Decay" property: *Fracture in the coronation of the central column, transversal to the central nave* (Figure 20).

4.6.6. Risk Assessment

Another important phase in the conservation processes of a historic building is the performance of risk assessment tasks, mainly aimed at the tasks of recognition and understanding of pathological processes, as well as the design of appropriate construction solutions for repair. These procedures can be substantially reinforced by the improvement in the methodological process. The HBIM project should facilitate these processes in an interdisciplinary process, containing the specific properties suitable for this stage. The Duomo HBIM has gone through a phase of auscultation and previous studies, in which visual prospection has been of great importance, complemented, or not, with diagnostic tests. Continuing with the example given, the mark that outlines the detachment of ashlar has been mapped with the classification by "subdivisions" (zonings agreed by the discipline): *AUE.010 Auscultation and trials, subdivision 1* (SCFClass.V2); it was enriched with the enabled properties of the Risk Assessment category. Figure 21 has selected the Activity category property, showing all the options available for its markup: Visual, Empirical, Instrumental, Laboratory test, Action, Intervention, Preliminary activity, Preconsolidation, Cleaning (restoration), Consolidation, Integration, Protection, Disassembly/Reassembly, and Cleaning (Housekeeping). For the "Activity type" property, the following options have been selected: Re-adhesion by pins, Stuffed same material. All the properties established with their selected items or options are collected in an HBIM project schema (Table 3).

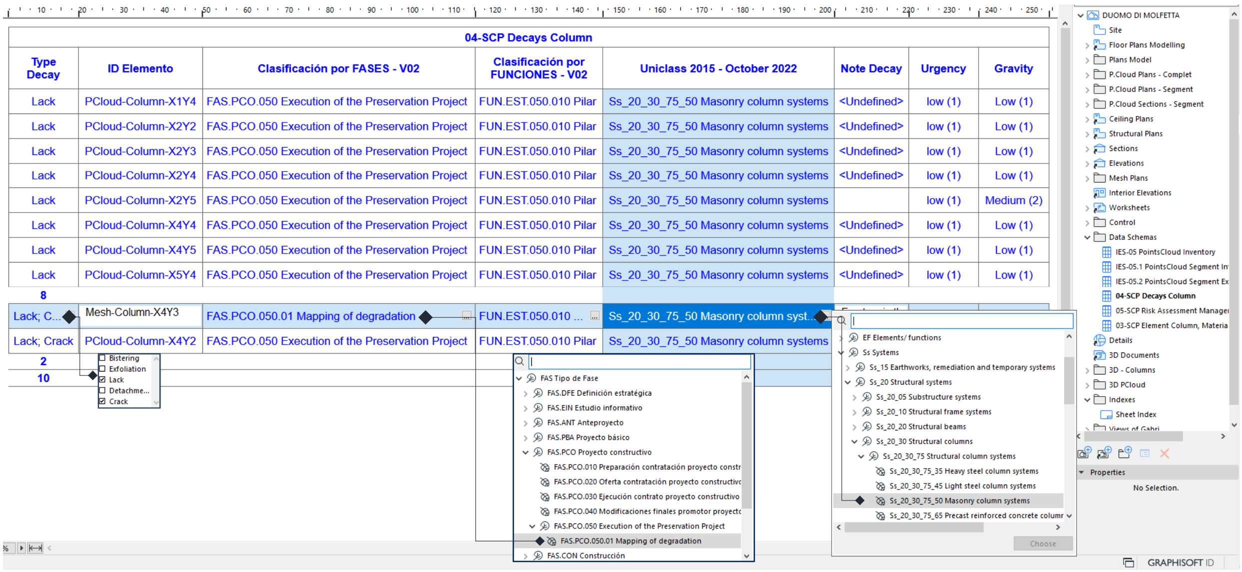


Figure 19. The diagram showing the Decays of the columns of the Duomo. All columns are classified by their Structural Function and Phase Execution of the Preservation Project.

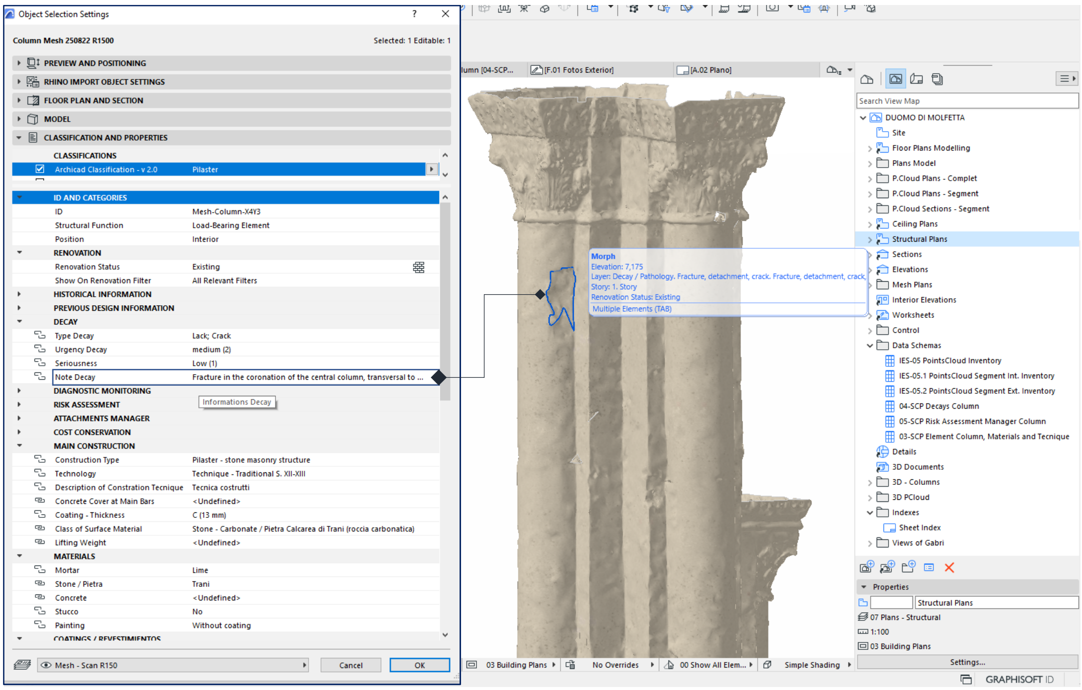


Figure 20. The Object Selection Settings of Column-X4Y3, with the properties of Preservation Processes. In the category Decay: Type, Urgency, Seriousness and Note Decay (fracture in the coronation of the central column, transversal to the central nave).

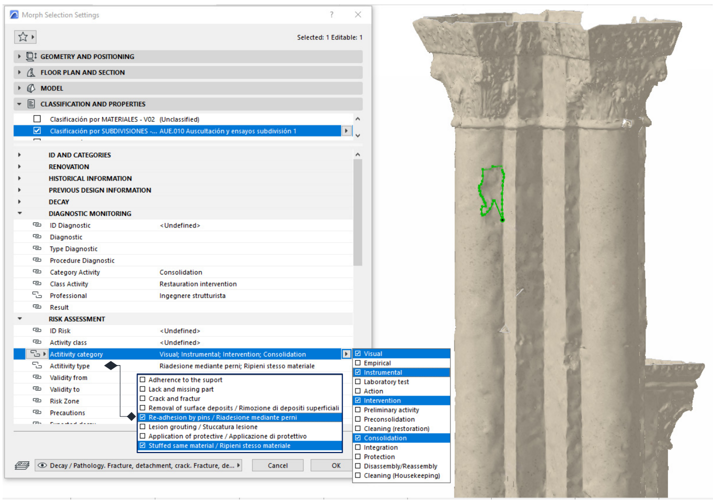


Figure 21. The mark of deterioration is enriched with the properties of the Risk Assessment category. For the Activity category: Visual, Instrumental, Intervention, and Consolidation. In Activity type: Re-adhesion by pins, Stuffed same material.

Table 3. The scheme Risk Assessment Manager Column and Pilaster of the HBIM Duomo di Molfetta project, exported in format xlsx (the design of the scheme, made in the HBIM project itself, is maintained).

05-SCP Risk Assessment Manager Column/Pilaster (Pag.1)								
ID Risk (String)	**ID Elemento BIM**	**Uniclass 2015—October 2022**	**Type Decay**	**Activity Type**	**Activity Class**	**Activity Category**	**Risk Zone**	**Interactions (Option Set)**
Ri-001.F1.PR019	Mesh-Column-X4Y3	Ss_20_30_75_50 Masonry column systems	Lack; Crack	Lack and missing part; Crack and fractur	Control/Inspection; Inspection	Visual	Partial element	With the horizontal support structure.
Ri-002.F1.PR019	PCloud-Column-X4Y2	Ss_20_30_75_50 Masonry column systems	Lack; Crack	Lack and missing part	Control/Inspection; Inspection	Visual; Empirical	Whole element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X1Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
ARi-003.F1.PR019	PCloud-Column-X2Y2	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X2Y3	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part; Crack and fractur	Control/Inspection; Inspection	Visual; Instrumental	Whole element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X2Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X2Y5	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X4Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X4Y5	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.
Ri-003.F1.PR019	PCloud-Column-X5Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element	With the horizontal support structure.

Table 3. *Cont.*

05-SCP Risk Assessment Manager Column/Pilaster (pag.2)								
ID Risk (String)	**ID Elemento BIM**	**Precautions**	**Validity from**	**Validity to**	**Construction Type (Option Set)**	**Technology (Option Set)**	**Class of Surface Material (Option Set)**	**Mortar**
Ri-001.F1.PR019	Mesh-Column-X4Y3	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-002.F1.PR019	PCloud-Column-X4Y2	<?>	25 July 2023	Open	Column—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X1Y4	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X2Y2	<?>	25 July 2023	Open	Column—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X2Y3	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X2Y4	<?>	25 July 2023	Open	Pilaster—brick masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X2Y5	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X4Y4	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X4Y5	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime
Ri-003.F1.PR019	PCloud-Column-X5Y4	<?>	25 July 2023	Open	Pilaster—stone masonry structure	Technique—Traditional S. XII-XIII	Stone—Carbonate/Pietra Calcarea di Trani (roccia carbonatica)	Lime

4.6.7. Data Interoperability with Conservation Specialists

To make collaboration with agents external to the Teamwork HBIM team more flexible, workflow interoperability is solved with the export of schema data in Excel (xlsx) formatted tables. In this way, the specialist fills in the items of the auscultation with their variables, previously established or incorporating some new ones according to the criteria of the specialist collaborator. The completed and revised tables are then imported into the HBIM project, automatically updating all the data. The interoperability process does not require programming processes as it is based on simple interactive schemas that incorporate the appropriate pre-established properties. The types of schematic will vary depending on the category of the data and the tasks to be carried out by the inspector and/or operator: inspection, control, monitoring, diagnosis of the crack or seat (decay), materials and techniques applied in the intervention, etc. Table 4 shows the risks detected in the columns and have been linked to the point cloud fractions, incorporating the items, type decay, activity (type, class, category), and risk zone, with the possibility of selecting the appropriate option.

Table 4. Editing the data schema exported in Excel format (xlxs) from Archicad, Interoperability>Classification and Properties option> Exports property values from the schema.

ID Risk (String)	ID Elemento BIM	Uniclass 2015—October 2022	Type Decay (Option Set)	Activity Type (Option Set)	Activity Class (Option Set)	Activity Category (Option Set)	Risk Zone (Option Set)
Ri-001.F1.PR019	Mesh-Column-X4Y3	Ss_20_30_75_50 Masonry column systems	Lack; Crack	Lack and missing part; Crack and fractur	Control; Inspection	Visual	Partial element
Ri-002.F1.PR019	PCloud-Column-X4Y2	Ss_20_30_75_50 Masonry column systems	Lack; Crack	Lack and missing part	Control; Inspection	Visual; Empirical	Whole element
Ri-003.F1.PR019	PCloud-Column-X1Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X2Y2	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X2Y3	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part; Crack and fractur	Control; Inspection	Visual; Instrumental	Whole element
Ri-003.F1.PR019	PCloud-Column-X2Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X2Y5	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X4Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X4Y5	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element
Ri-003.F1.PR019	PCloud-Column-X5Y4	Ss_20_30_75_50 Masonry column systems	Lack	Lack and missing part	Inspection	Visual	Partial element

5. Discussion

Nowadays, BIM platforms represent a great opportunity to serve as a collaborative workflow in the management of architectural and artistic heritage, to which it should be added that they currently satisfactorily support the data from TDP, UAV, and TLS surveys, in the form of a cloud of points and processed surfaces, providing the possibility of observing and analyzing structural deformations, cavities, and fissures common in a historic building. This potential must be exploited in this perpetuated scientific quest to implement mechanisms of analysis and records that can last over time. The insertion of this faithful data in the BIM project makes them parameterizable, being able to incorporate all kinds of semantic properties; therefore, the conservation of CH based on a graphic-semantic information model or HBIM becomes a very effective recording process. The methodology developed above is in line with the search for the maximum convergent direction towards the representation of a digital twin model of architectural heritage.

The first step to be established, before proceeding to an organizational structure of an HBIM project, is the identification and classification of the components and elements. The semantic classification, according to the standards of the area or country, structures the elements for the subsequent realization of the segmentation, although they are still limited in very specific elements of historical architecture as they are not common or standardized construction systems today. The post-processed information of the massive data is usually provided as a global point cloud, georeferenced in the same global system, so it is convenient to subdivide it for better management, both to improve the performance of the computer and to have all the elements well organized and classified. This procedure would facilitate the subsequent auscultation of the element as it is delimited, as well as the parametric modeling of it, the analytical study of its materials and deterioration, and the association of intrinsic parameters so that they can be evaluated by all the intervening agents.

One of the difficulties that has arisen in the study is that the algorithms available to automate the tasks of identification and segmentation of architectural elements, although they facilitate the tasks of selection and classification of surfaces such as walls, floors, ceilings, and pure geometric shapes present certain difficulties in detecting characteristic pieces that incorporate decorative motifs. These elements are classified in the category of others, although it is in this classification that the bulging and overhanging of surfaces that do not follow a geometric rule are also recorded. In the case study, this point discrimination has been used for the detection and proper classification of deterioration. Although it should be noted that currently the assistance and interpretation of the expert operator is still essential to achieve accurate results, as CH is still orphaned of automatic classification algorithms that allow its specific typologies to be accurately detected.

Regarding Heritage Building Information Modeling from point cloud data (Scan-to-BIM), it is consolidated as an efficient and accurate process for the representation of heritage. But the difficulty lies in the fact that these historical constructions generally have complex geometry and shapes. The work of accurate digital modeling of a historic building remains a challenge, even more so when looking for a faithful representation. For this reason, it has been investigated to apply in a general way a flexible and productive methodology, not exceeding the LOD 200 level in the details of parametric elements of the Duomo di Molfetta, although complemented with the semantic data provided by the TLS and SFM techniques. The semantic and structured segmentation of the global point cloud provided by TLS has been efficiently exploited, using the portions obtained from the process as containers of faithful graphic information (geometry and materiality), even containing the specific parameters for conservation work. The point cloud portion behaves like another parametric object, except that the surface is made up of a succession of 3D points. It will be the conditions of the environment at the time of scanning and the resolution of the equipment (scanner/camera) that will mark the quality of the graphic representation. Although it should not be forgotten that the most outstanding potential of the HBIM methodology lies in the efficient and interdisciplinary management of cultural heritage documentation; the project created has met these expectations.

Finally, the 3D model contained in the HBIM project has been enriched by parametric elements obtained by various processes: the architectural-constructive typology of the historic building is represented globally as a simple parametric object; for certain objects identified with deterioration, they have been transformed into a polygonal mesh of the enveloping geometry; and, with regard to point clouds, the initial unstructured information provided by the TLS survey has been transformed into well-identified portions classified by typologies. Based on precise and organized semantic segmentation, it has been possible to develop the usual conservation processes, such as the identification of degradation, marking and labeling of deterioration (decays), risk assessment, and data interoperability with conservation specialists.

Limitations of the Research

One of the great problems that point cloud classification procedures solve is the dissection of each of the elements of a complex historical architecture as a whole. The semi-automatic boxing procedure in Cyclone 3DR can be effective for basic structuring, but it fails to fully solve semantic segmentation. There are configuration problems in the elements embedded in the walls, such as cornices, which require box procedures that need to be improved.

We can consider that the classification of the units of the box is useful to establish schemes that facilitate the work between the point cloud and the parametric objects. It is uncommon in segmentation work to organize the entire classification in the way that is presented here. However, it is important to note that this work constitutes the beginning of a discrete workflow between complex elements and their parametric modeling. It is also necessary to define a roadmap in order to integrate the deviations analyzed by precision software into the BIM model in the future. This could be related to semantic interoperability.

6. Conclusions

This research has justified the significant potential of the integration of TLS and photogrammetric scan data into the HBIM project to facilitate the conservation and restoration of artistic and architectural heritage, as demonstrated by the case study of the Duomo di Molfetta. Based on the results obtained, it can be concluded that the methodological process is very valid to be applied to buildings and historical assets, facilitating the complex process of identification and semantic segmentation in this field. In an HBIM project, generic typological elements of classical architecture may coexist, where there are recurrent classes that are supported by proportional rules (and therefore easy to parameterize), with others specific to a style characteristic of the time or geographical place and that contain complex geometries. The latter will be represented by the point clouds themselves or transformed into mesh surfaces for the faithful representation of the envelope. Any of the routes taken will never hinder the tasks of auscultation, control, maintenance, and intervention.

The management of the usual deterioration in a historic building of this category is efficiently extended to all the agents of the multidisciplinary team. The 3D model incorporates not only faithful architectural details, but also supports up-to-date semantic data, optimizing the preservation of cultural heritage. The schemas with the appropriate properties for the analysis and conservation tasks are transmitted to the collaborators of the Teamwork project (Archicad), as well as to external specialists both in data tables (Excel Microsoft format) and in intrinsic values of the elements of the OpenBIM model (IFC format).

The methodological process described above facilitates the perfect integration of the most advanced current technologies, facilitating the most correct decision-making in the usual tasks of preservation and restoration. Bearing in mind the multidisciplinary participation in the conservation of CH, the HBIM project endorses the interoperability of data and therefore the interdisciplinary collaboration and participation of all specialist agents and other stakeholders. It is this way of preserving throughout the life cycle of the historic building that the protection of Italy's rich architectural and artistic heritage is guaranteed.

As future lines of research, we want to take advantage of the knowledge and skills acquired in this research to continue perfecting the methodological process in search of greater automation and the perfection of rigid and rudimentary processes of semantic modeling. We have verified that the machine learning classification algorithms, which Cyclone 3DR incorporates in its Automatic Classification tool, are not trained for the typologies of historical architecture, mainly in identifying the components of columns (base, shaft, capital), projecting elements in walls (cornices, bulges, shelf), diversity of openings in walls (doors, windows and niches), and the great variety of vaulted ceilings, as well as the discrimination of artistic elements and furniture in flooring (altars, benches, cabinets) and walls (paintings, sculptures, altarpieces, chandeliers, lighting elements). For this reason and being aware of the importance of the information provided by LIDAR techniques, it is necessary to continue exploring the best implementation of AI in the semantic segmentation of data to obtain adequate structuring of historical information. There are very recent works that have started this path of research as a new roadmap [50], where it was possible to verify how specifically geomatic engineering software is designed for an incipient classification of new works.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs16234542/s1. The sections taken from the report to compare the point clouds with the theoretical surface of Column-X4Y2 shaft (Cyclone 3DR). The data of the deviations in each horizontal section given to the shaft of Column-X4Y2.

Author Contributions: Conceptualization, E.N.-J. and S.B.; methodology, E.N.-J.; software, E.N.-J.; validation, J.M., E.N.-J. and S.B.; formal analysis, J.M., E.N.-J. and S.B.; investigation, J.M., E.N.-J. and S.B.; resources, E.N.-J. and S.B.; data curation, E.N.-J. and S.B.; writing—original draft preparation, E.N.-J.; writing—review and editing, E.N.-J. and J.M.; visualization, E.N.-J.; supervision, E.N.-J., J.M.

and S.B.; project administration, E.N.-J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the research and complement the information are available for consultation by interested parties. Access to the specific information must be requested in advance from the authors.

Acknowledgments: We would like to express our sincere thanks to Gabriel Tena Maireles, an excellent student at the School of Building Engineering of the University of Seville, for his help in the modeling work of the HBIM project of the Duomo di Molfetta.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Miceli, A.; Morandotti, M.; Parrinello, S. 3D survey and semantic analysis for the documentation of built heritage. The case study of Palazzo Centrale of Pavia University. *VITRUVIO-Int. J. Archit. Technol. Sustain.* **2020**, *5*, 65–80. [CrossRef]
2. Moyano, J.; Nieto-Julián, J.E.; Bienvenido-Huertas, D.; Marín-García, D. Validation of Close-Range Photogrammetry for Architectural and Archaeological Heritage: Analysis of Point Density and 3D Mesh Geometry. *Remote Sens.* **2020**, *12*, 3571. [CrossRef]
3. Spina, S.; Debattista, K.; Bugeja, K.; Chalmers, A. Point Cloud Segmentation for Cultural Heritage Sites. In Proceedings of the VAST'11: Proceedings of the 12th International Conference on Virtual Reality, Archaeology and Cultural Heritage, Prato, Italy, 18–21 October 2011; pp. 41–48.
4. Costantino, D.; Pepe, M.; Restuccia, A. Scan-to-HBIM for conservation and preservation of Cultural Heritage building: The case study of San Nicola in Montedoro church (Italy). *Appl. Geomat.* **2023**, *15*, 607–621. [CrossRef]
5. Rocha, G.; Mateus, L.; Fernández, J.; Ferreira, V. A Scan-to-BIM Methodology Applied to Heritage Buildings. *Heritage* **2020**, *3*, 47–67. [CrossRef]
6. de la Plata, A.R.M.; Franco, P.A.C.; Franco, J.C.; Bravo, V.G. Protocol Development for Point Clouds, Triangulated Meshes and Parametric Model Acquisition and Integration in an HBIM Workflow for Change Control and Management in a UNESCO's World Heritage Site. *Sensors* **2021**, *21*, 1083. [CrossRef] [PubMed]
7. Alessandri, L.; Baiocchi, V.; Del Pizzo, S.; Rolfo, M.F.; Troisi, S. Photogrammetric survey with fisheye lens for the characterization of the La Sassa cave. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W9*, 25–32. [CrossRef]
8. Di Stefano, F.; Malinverni, E.S.; Pierdicca, R.; Fangi, G.; Ejupi, S. HBIM implementation for an ottoman mosque. Case of study: Sultan mehmet fatih II mosque in Kosovo. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W15*, 429–436. [CrossRef]
9. Moyano, J.; Justo-Estebaranz, Á.; Nieto-Julián, J.E.; Barrera, A.O.; Fernández-Alconchel, M. Evaluation of records using terrestrial laser scanner in architectural heritage for information modeling in HBIM construction: The case study of the La Anunciación church (Seville). *J. Build. Eng.* **2022**, *62*, 105190. [CrossRef]
10. Klapa, P.; Gawronek, P. Synergy of Geospatial Data from TLS and UAV for Heritage Building Information Modeling (HBIM). *Remote. Sens.* **2022**, *15*, 128. [CrossRef]
11. Maté-González, M.Á.; Di Pietra, V.; Piras, M. Evaluation of Different LiDAR Technologies for the Documentation of Forgotten Cultural Heritage under Forest Environments. *Sensors* **2022**, *22*, 6314. [CrossRef]
12. Pérez, J.J.; Senderos, M.; Casado, A.; Leon, I. Field Work's Optimization for the Digital Capture of Large University Campuses, Combining Various Techniques of Massive Point Capture. *Buildings* **2022**, *12*, 380. [CrossRef]
13. Tapete, D.; Casagli, N.; Luzi, G.; Fanti, R.; Gigli, G.; Leva, D. Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments. *J. Archaeol. Sci.* **2013**, *40*, 176–189. [CrossRef]
14. Zhou, W.; Chen, F.; Guo, H. Differential Radar Interferometry for Structural and Ground Deformation Monitoring: A New Tool for the Conservation and Sustainability of Cultural Heritage Sites. *Sustainability* **2015**, *7*, 1712–1729. [CrossRef]
15. Tang, P.; Chen, F.; Zhu, X.; Zhou, W. Monitoring Cultural Heritage Sites with Advanced Multi-Temporal InSAR Technique: The Case Study of the Summer Palace. *Remote Sens.* **2016**, *8*, 432. [CrossRef]
16. Drougkas, A.; Verstrynge, E.; Van Balen, K.; Shimoni, M.; Croonenborghs, T.; Hayen, R.; Declercq, P.-Y. Country-scale InSAR monitoring for settlement and uplift damage calculation in architectural heritage structures. *Struct. Health Monit.* **2021**, *20*, 2317–2336. [CrossRef]
17. Su, R.; Ma, J. Research on the Protection of Architectural Heritage Based on SBAS and LSTM Technologies. In *2023 IEEE International Conference on Image Processing and Computer Applications (ICIPCA)*; IEEE: Piscataway, NJ, USA, 2023; pp. 1149–1157. [CrossRef]
18. Barazzetti, L.; Binda, L.; Scaioni, M.; Taranto, P. Photogrammetric survey of complex geometries with low-cost software: Application to the 'G1′ temple in Myson, Vietnam. *J. Cult. Herit.* **2011**, *12*, 253–262. [CrossRef]
19. Herban, S.; Costantino, D.; Alfio, V.S.; Pepe, M. Use of Low-Cost Spherical Cameras for the Digitisation of Cultural Heritage Structures into 3D Point Clouds. *J. Imaging* **2022**, *8*, 13. [CrossRef]

20. Grussenmeyer, P.; Alby, E.; Landes, T.; Koehl, M.; Guillemin, S.; Hullo, J.F.; Assali, P.; Smigiel, E. Recording approach of heritage sites based on merging point clouds from high resolution photogrammetry and terrestrial laser scanning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *XXXIX-B5*, 553–558. [CrossRef]
21. Fryskowska, A.; Stachelek, J. A no-reference method of geometric content quality analysis of 3D models generated from laser scanning point clouds for hBIM. *J. Cult. Herit.* **2018**, *34*, 95–108. [CrossRef]
22. Mostafavi, A.; Scaioni, M.; Yordanov, V. Photogrammetric solutions for 3d modeling of cultural heritage sites in remote areas. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-4/W18*, 765–772. [CrossRef]
23. Yastikli, N. Documentation of cultural heritage using digital photogrammetry and laser scanning. *J. Cult. Herit.* **2007**, *8*, 423–427. [CrossRef]
24. Jaradat, M.; Al Majali, H.; Bendea, C.; Bungau, C.C.; Bungau, T. Enhancing Energy Efficiency in Buildings through PCM Integration: A Study across Different Climatic Regions. *Buildings* **2023**, *14*, 40. [CrossRef]
25. Galantucci, R.A.; Musicco, A.; Bruno, S.; Fatiguso, F. Automatic detection of dampness phenomena on architectural elements by point cloud segmentation. In Proceedings of the Rehabend 2020 Euro-American Congress-Construction Pathology, Rehabilitation Technology and Heritage Management, Granada, Spain, 24–27 March 2020; pp. 1141–1189.
26. Rodrigues, F.; Cotella, V.; Rodrigues, H.; Rocha, E.; Freitas, F.; Matos, R. Application of Deep Learning Approach for the Classification of Buildings' Degradation State in a BIM Methodology. *Appl. Sci.* **2022**, *12*, 7403. [CrossRef]
27. Matrone, F.; Martini, M. Transfer learning and performance enhancement techniques for deep semantic segmentation of built heritage point clouds. *Virtual Archaeol. Rev.* **2021**, *12*, 73–84. [CrossRef]
28. Muñoz-Pandiella, I.; Akoglu, K.; Bosch, C.; Rushmeier, H. Towards Semi-Automatic Scaling Detection on Flat Stones. In Proceedings of the EUROGRAPHICS Workshop on Graphics and Cultural Heritage, Graz, Austria, 27–29 September 2017. [CrossRef]
29. Peng, S.-H.; Nam, H.-D. A Robust Crack Filter Based on Local Gray Level Variation and Multiscale Analysis for Automatic Crack Detection in X-ray Images. *J. Electr. Eng. Technol.* **2016**, *11*, 1035–1041. [CrossRef]
30. Sánchez, J.; Quirós, E. Semiautomatic detection and classification of materials in historic buildings with low-cost photogrammetric equipment. *J. Cult. Herit.* **2017**, *25*, 21–30. [CrossRef]
31. Kong, X.; Hucks, R.G. Preserving our heritage: A photogrammetry-based digital twin framework for monitoring deteriorations of historic structures. *Autom. Constr.* **2023**, *152*, 104928. [CrossRef]
32. Boonpook, W.; Tan, Y.; Xu, B. Deep learning-based multi-feature semantic segmentation in building extraction from images of UAV photogrammetry. *Int. J. Remote. Sens.* **2021**, *42*, 1–19. [CrossRef]
33. Fischler, M.A.; Bolles, R.C. Random sample consensus. *Commun. ACM* **1981**, *24*, 381–395. [CrossRef]
34. Raguram, R.; Frahm, J.-M.; Pollefeys, M. A comparative analysis of RANSAC techniques leading to adaptive real-time random sample consensus. In *Computer Vision—ECCV 2008: 10th European Conference on Computer Vision, Marseille, France, 12–18 October 2008*; Proceedings, Part II; Springer: Berlin/Heidelberg, Germany, 2008; pp. 500–513.
35. Dong, Z.; Yang, B.; Hu, P.; Scherer, S. An efficient global energy optimization approach for robust 3D plane segmentation of point clouds. *ISPRS J. Photogramm. Remote. Sens.* **2018**, *137*, 112–133. [CrossRef]
36. Vo, A.-V.; Truong-Hong, L.; Laefer, D.F.; Bertolotto, M. Octree-based region growing for point cloud segmentation. *ISPRS J. Photogramm. Remote Sens.* **2015**, *104*, 88–100. [CrossRef]
37. Kim, C.; Habib, A.; Pyeon, M.; Kwon, G.-R.; Jung, J.; Heo, J. Segmentation of Planar Surfaces from Laser Scanning Data Using the Magnitude of Normal Position Vector for Adaptive Neighborhoods. *Sensors* **2016**, *16*, 140. [CrossRef]
38. Moyano, J.; León, J.; Nieto-Julián, J.E.; Bruno, S. Semantic interpretation of architectural and archaeological geometries: Point cloud segmentation for HBIM parameterisation. *Autom. Constr.* **2021**, *130*, 103856. [CrossRef]
39. Croce, V.; Caroti, G.; De Luca, L.; Jacquot, K.; Piemonte, A.; Véron, P. From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. *Remote Sens.* **2021**, *13*, 461. [CrossRef]
40. Leica Cyclone 3DR (leica-geosystems.com). 2024. Available online: https://shop.leica-geosystems.com/it/es-ES/leica-blk/software/leica-cyclone-3dr/buy (accessed on 3 August 2024).
41. Tzedaki, V.; Kamara, J.M. Capturing As-Built Information for a BIM Environment Using 3D Laser Scanner: A Process Model. In Proceedings of the Architectural Engineering Conference AEI 2013, State College, PA, USA, 3–5 April 2013; pp. 486–495. [CrossRef]
42. Radanovic, M.; Khoshelham, K.; Fraser, C. Geometric accuracy and semantic richness in heritage BIM: A review. *Digit. Appl. Archaeol. Cult. Herit.* **2020**, *19*, e00166. [CrossRef]
43. Liu, J.; Xu, D.; Hyyppa, J.; Liang, Y. A Survey of Applications With Combined BIM and 3D Laser Scanning in the Life Cycle of Buildings. *IEEE J. Sel. Top. Appl. Earth Obs. Remote. Sens.* **2021**, *14*, 5627–5637. [CrossRef]
44. Moyano, J.; Gil-Arizón, I.; Nieto-Julián, J.E.; Marín-García, D. Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage. *J. Build. Eng.* **2022**, *45*, 103274. [CrossRef]
45. Moyano, J.; Carreño, E.; Nieto-Julián, J.E.; Gil-Arizón, I.; Bruno, S. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Autom. Constr.* **2022**, *143*, 104551. [CrossRef]
46. Nieto-Julián, J.E.; Lara, L.; Moyano, J. Implementation of a TeamWork-HBIM for the Management and Sustainability of Architectural Heritage. *Sustainability* **2021**, *13*, 2161. [CrossRef]

47. Moyano, J.; Pili, A.; Nieto-Julián, J.E.; Della Torre, S.; Bruno, S. Semantic interoperability for cultural heritage conservation: Workflow from ontologies to a tool for managing and sharing data. *J. Build. Eng.* **2023**, *80*, 107965. [CrossRef]
48. Railway Innovation Hub, AEI. Agrupaciones Empresariales Innovadoras, M. y A. U. Ministerio de Transportes, and Adif. Administrador de Infraestructuras Ferroviarias. BIM Railway Classification System SCFclass. Available online: https://www.railwayinnovationhub.com/bim/ (accessed on 16 February 2024).
49. NBS Enterprises Ltd. Uniclass—Unified Classification for the Construction Industry. Available online: https://uniclass.thenbs.com/ (accessed on 16 February 2024).
50. Moyano, J.; Musicco, A.; Nieto-Julián, J.E.; Domínguez-Morales, J.P. Geometric characterization and segmentation of historic buildings using classification algorithms and convolutional networks in HBIM. *Autom. Constr.* **2024**, *167*, 105728. [CrossRef]