

Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project

Juan Moyano^{a,*}, Eva Carreño^a, Juan E. Nieto-Julián^a, Ignacio Gil-Arizón^a, Silvana Bruno^b

^a Departamento de Expresión Gráfica e Ingeniería en la Edificación, Escuela Técnica Superior de Ingeniería de Edificación, Universidad de Sevilla, 4A Reina Mercedes Avenue, Seville 41012, Spain

^b Politecnico University of Bari, Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Via Edoardo Orabona, 4, 70125 Bari, Italy

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ABSTRACT

Working with heritage is complex and projects often include scientific, structural, and documentary studies. Every step requires a systematic approach in which the contribution of the diverse experts that participate in the conservation of heritage assets is analysed following the logical sequence of the project execution phase. However, there are still no scientific contributions that record the complete process. A logical sequence, called a 'systematic approach' in this paper, should start with data acquisition using remote sensing techniques, the insertion of point cloud data in a Building Information Modelling (BIM) environment, ontologies applied to HBIM (Historic BIM), data classification, and evolution towards the Digital Twin (DT) concept. This paper also analyses the modelling workflow of a case study, the construction of a column base of the Santiago church in Jerez de la Frontera (Spain). This component has been automatically modelled from a mesh in an Autodesk Revit family and through an adaptive mesh process in ArchiCAD. Furthermore, one of the objectives was the data organisation by following and extending a standard data structure of the column components. This paper presents a novel holistic approach from data capture, analysis of complex geometry, construction of the semantically enriched parametric model, and exchange of it among all involved professionals in open source IFC formats. This systematic approach therefore makes it possible to obtain a validated DT for the life-cycle management of architectural elements.

1. Introduction

Cultural heritage (CH) is an essential aspect in architectural research and knowledge. The complexity of the process to preserve cultural assets implies that new study perspectives and implementations are continuously suggested to reach the recommendations made by UNESCO in 1962. These were safeguarding landscapes, natural and anthropic environments, which are of cultural or aesthetic interest or constitute a harmonious, natural whole [1]. CH is a substantial and dynamic repository of knowledge considered as a unique and irreplaceable source of aesthetic, historical and cultural values [2] and should be documented to keep both the object and its knowledge. The multimedia technologies developed at late 1980s are useful to create digital models for architecture and engineering students. Both archaeology and architecture have taken advantage from these digital resources to improve management and dissemination processes, even using other technologies such as virtual reality [3,4]. Virtual reconstruction has taken an important place in the ways of representation and visualisation, bringing

new perspectives for research. Static representations, such as projection or perspective drawings, have been replaced by dynamic representations in which numerous modifiable parameters included in new and recent digital platforms take part. Three-dimensional (3D) digitisation is the creation of a 3D computer model in which the digital facet holds an essential place to create images, virtual representation, and building models of their phases [5]. Thanks to the evolution of the Computer-Aided Design (CAD) systems, which began in the 1980s, the vector graphic representation resulted in a more advanced and dynamic virtual model. However, the Architecture, Engineering and Construction (AEC) sectors required a new change to get closer to the efficiency of other production industries such as the automobile or the aeronautical industries. For this reason, at the beginning of the 21st century, processes began to be reformulated and a new technology to represent and manage construction was established. In this way, a new term, Building Information Modelling (BIM), emerged and gave name to the renewed 3D digital tools, recognised as BIM platforms (BIMP). The process is nowadays applied to the life cycle of buildings and civil infrastructure,

* Corresponding author.

E-mail address: jmoyano@us.es (J. Moyano).

becoming a work methodology that provides a new interdisciplinary view going beyond the simple creation of the design.

In CH, as in the AEC and Operation (AECO) sectors, the methodology describes the intervention and research process in both the archaeological site and the historic building. Therefore, BIM is an evolution of the traditional system based on orthogonal projections and perspectives in order to include new information units. The working process for an heritage asset is a complex set [2] in which many study variables take part, from the geometric, mechanical, chemical and physical analysis to the documentary study. Every step requires a systematic approach in which the various fields taking part in the conservation of the heritage asset are analysed from the same perspective, representing the logical sequence of the project execution phase. Recording a great amount of information during the conservation process requires the collaboration of professionals, with various specialists, and technical teams committed to the project execution. Today, the information of historic buildings is usually included in individual reports, each involving dispersed projects with datasets provided by various technical teams. In addition, the diversity of projects that can be executed on an historic building, such as conservation and restoration, adaptive reuse, preventive maintenance, documentary management, interpretation, and research, requires a systematic perspective. The BIM methodology applied to this context aims to solve these issues, including documentary management, geometric management, and the container of semantic information. The new approach to management and conservation related to historic buildings was called HBIM (Heritage Building Information Modelling) [6]. The application of HBIM in the CH domain has been mainly developed in three general lines: data capture in the BIM system, i.e., Scan to BIM; software implementation to develop parametric and similar designs; and finally, the construction of a semantically enriched digital model. Murphy et al. [6] and Dore and Murphy [7] firstly investigated the HBIM approach to convert it into the core of an architectural heritage intervention project. The benefits of this approach have subsequently been studied by other researchers [8–10]. Several literature review studies have examined the evolution of HBIM and current gaps in knowledge [11,12]. Later, some publications were related to HBIM modelling procedures [13]; López et al. [14] explored the effectiveness and the usefulness of the different methodologies that were developed to model families of elements of interest; while, Radanovic et al. [15] reviewed methods for geometric accuracy evaluation and semantic richness. Silvana Bruno et al. [16] proposed an approach for diagnosis and performance assessment of architectural works within the HBIM methodology. Khalil and Stravrovadis [17] studied the state of the art of HBIM in the various data domains that can be included in the research and documentary process of built heritage. Nevertheless, these studies do not discuss methodologies to build a complete HBIM useful to support all the stages of restoration and valid for life-cycle management. In this way, this paper aims to define a novel systematic approach to generate Historical Building Information Modelling (HBIM) in the architectural restoration project.

In this overviewed context, modelling has been considered as a digital representation that includes the geometric and simplified properties of a building, archaeological site, or object. These models immediately represented the architecture designed in the three dimensions. The progress of BIM digital platforms implies including semantic components that are represented as digital objects with relations, attributes, and properties [18]; also, at the CH level, geometry plays an important role since most buildings present damages and structural deformations. Although the goals of BIM regarding CH do not include a design phase, it could be useful to enrich the knowledge of the building [19], thus facilitating the management of the information throughout the years. However, geomatics plays an outstanding role in the 3D digital reconstruction, the accuracy of the model dimensions, and their reliability. The most important aspect to transfer the geometric information to a 3D model is the reverse engineering process [20]. This process based on obtaining the ideal geometric parametric model, i.e., obtaining the

geometric properties of the element by scanning, is among the unsolved problems. Most scientific studies on HBIM have highlighted the importance of transferring point cloud data from the survey to the 3D parametric modelling in BIM platforms [21,22]. There are adaptability studies of Scan to BIM [23–25]. For instance, the latest works on automation in HBIM parametric modelling from point clouds were carried out by Andriasyan et al. [26] and by Constantino et al. [27] in the Rhino environment for Revit. Other studies have shown the potential of Terrestrial Laser Scanning (TLS) for indoor spaces data segmentation [28–30], and other research works reinforced the creation of 3D models based on terrestrial images [31]. This means obtaining a subset of classification points that are useful for the 3D modelling, but this workflow requires the use of independent software and additional components that could hinder the process.

Another interesting issue is whether the DTs, turned into parametric elements, should be structural or elemental units when they are in BIM platforms, i.e., to what extent the architectural elements should be semantically segmented. A pillar of a church could be a structural unit, but its parts are structured in masonry ashlar and cornices. Thus, the following questions arise: Where the parametric subsets should be established? How the semantic classification of these pieces should be interpreted? Establishing a knowledge limit, i.e., the intended Level of Development (LoD) for the HBIM project, defines the semantic classification [22]. Capone and Lanzara [23] established two approaches to create an HBIM system: the simplified identification of the shape grammar by compiling objects of the library and the construction of the geometry itself. The hypothesis considered is the identification of both architectural rules and form. Nonetheless, the operator modelling should consider the structural units in which the point cloud is going to be segmented and correlate the information of the construction historical knowledge with the information provided by the point cloud. Thus, the operator segmenting should have a deep knowledge of both the structure and the construction units of the building. The original, irregular and detailed forms are often modelled with an excessive simplification instead of semi-automatically from point clouds using algorithms as in [32]. The simplified approach implies using geometries away from parametric object libraries that represent ideal models or shapes based on plane profiles or sections [33,34]. Therefore, the 3D reconstruction, either manually or semi-automatically, is not always exhaustive. The digital representation of a surface that is not already treated does not have semantic properties, i.e., a mesh with textures is not a classified parametric object before being included in a BIM platform. When the surface is included in BIM, it turns into an object and could have its own attributes, except editable properties, thus implying that the mesh is part of the 3D model when generating parametric elements and can be enriched from a semantic point of view. This area of knowledge aims for objects to have extensive properties and characteristics. Most BIM digital platforms are not effective to apply native forms of complex shapes because interfaces do not provide such flexibility. However, some attempts have been made to create practical methodologies including open Application Programming Interfaces (APIs) to address the interoperability of complex geometry [35]. Some techniques, following command sequences in various software, enable the creation of parametric models from point clouds. According to Bruno [19], the ways of representing a 3D model could be mesh surfaces, NURBS surfaces, B-Rep surfaces, CSG, and parametric objects. This classification is appropriate, although some authors include B-Rep, swept solid, CSG, and clipping for IFC in the representation methods [36]. Meshes are surfaces described by a set of vertexes, edges and sides that defines a polyhedron object. Although meshes could be generated using various reverse engineering software such as Agisoft Metashape, CloudCompare, Geomagic Design X and MeshLab, triangulated meshes must first be converted to NURBS curves and surfaces for transformation into a parametric element. In this way, the adaptation of the sides of the object is eased, and Rhinoceros is the software par excellence for this. Regarding NURBS, some intervention works on architectural heritage

have included point clouds in BIM platforms by using a programme to manage the scan data. The 3D model of the Collemaggio Basilica is an example of this [37]. This study divided the structural elements by following the construction logic of the building, i.e., columns, walls, vaults, wooden elements of the roof, stone ashlars, and decorative elements were created through Boolean operations and NURBS surfaces from Rhinoceros software. For its part, B-Rep can be considered as a wireframe extension, but it has been used for limited goals. Zhu et al. [36] used B-Rep to convert essential data between BIM and GIS. Solihin et al. [38] also used CSG and B-Rep for parametric goals in an IFC. Consequently, ideal primitive geometries are solved in BIM, but not the adaptability of complex geometric shapes, a field that still needs to be studied. Most of the studies that address the complexity of geometry focus on solving this specific problem, but without defining strategic methodologies in a general context. In this research, this problem is approached in a broader sense that includes all the steps (the accurate geometric survey, the evaluation of the model built, the record based on ontologies, and the representation and export to IFC). This systematic approach, in which different technical teams take part, e.g., engineers and restorers, includes geomatics and the graphic representation and preservation of heritage. The BIM methodology is developed through various processes. Firstly, the construction of the 3D parametric model that could provide an ideal model built from a point cloud without considering Scan-to-BIM flows or creating DTs. This involves a major software interoperability effort to obtain an actual 3D parametric twin model. The 3D parametric model aims to provide a static geometry of objects whose shape can be modified and the numeric values of the set of parameters can be changed [39]. Secondly, the information model includes a database with attributes, materials, and geometry-related entities [40]. Thirdly, the 3D model integrates semantic information on aspects related to the history of the CH restoration. Finally, the model is exported for further processing in IFC.

2. Historic scope

2.1. Overview

Santiago Church in Jerez de la Frontera (Fig. 1) is selected as case study to validate the approach proposed in this paper. This church, among the bordering churches of the Cathedral of Seville, is in the late Gothic style. Its origin is a small chapel from the 13th century to which three side naves were added in the 15th century, thus forming the current temple [41]. The church was designed by Alonso Rodríguez, the master builder of the Cathedral of Seville [42]. This reflects the similarity of their columns [43], the quadripartite vaults, except the apse and



Fig. 1. Main façade of the church in 2018.

the first section, the three naves (central, higher and deep) ending in a polygonal head, and the hall church. The construction of the temple may have started some time before 1496 and was mostly completed twenty-five years later [44]; however, it was totally finished in the 17th century by Diego Moreno Meléndez, the architect and master builder of the church. As shown by Rodríguez-Mayorga et al. [41], the church has been restored throughout the years, although this paper is focused on the latest intervention by the architect Emilio Yanes in the pillar no.5 of the central nave. The technical team commenced the restoration work in 2007 when there was a concerning detachment of the church façade; works finished in 2016 after two years of inactivity. A structural analysis was carried out in 2005 revealed that the masonry damage was essentially due to two causes: partial collapses in the 17th and 19th centuries and the replacement of two pillars in the central nave in 1902 [41]. The diagnosis was published by Rodríguez-Mayorga et al. [45], who focused on the suitability of the grout injection with sleeve port pipe in the masonry structure.

The intervention in the building is written in three subsections in relation to the elements studied.

2.2. Analysis of the structural effects of the Santiago Church in Jerez de la Frontera

From the beginning, the analysis of the main deterioration of the temple was studied by Rodríguez-Mayorga [46]. This doctoral dissertation attributed the causes of the problems of the temple to six main aspects: i) the lack of symmetry in the spatial organisation of the church; ii) the difference between mass of volumes within the church compound; iii) the agglutination or lack of elements; iv) the incorporation of ornamental elements after its construction to magnify the trends of that period; v) material degradation and the presence of underground water resulting in a loss of loadbearing capacity of the masonry; and vi) geologic and meteorological actions that affect the collapse of the church.

2.3. Interventions

Rodríguez-Mayorga et al. [41,45] described the interventions and repairs carried out after finishing the temple, and this research is focused on the intervention of the column located in the entrance of the church, next to the main entry in the epistle nave. The column is called column number 5. It was built in limestone by the master builder Rafael Esteve, also a municipal architect, in 1905. At this time, Esteve proposed the reinforcement of the pillar by means of a series of wooden boards, along the perimeter of the shaft and tightened using steel clamps to compress the pillar. Afterwards, in the 21st century, with the development of the works in 2016, consolidation works were carried out to find out that this pillar was one of the most deteriorated. The first actions taken were previous works based on security and topographic control. Detachments took place in the façade during the beginning of the 21st century, so the temple was closed to conduct restoration works. All processes studying the restoration of this type of church require a methodology that follows the initial part represented in the workflow of Fig. 3; the historic building is better known thanks to an operational evaluation, a historical analysis, a topographic analysis, and data acquisition phase. This part could also be completed by developing structural statistical models.

2.4. Intervention in column 5

One of the first works was the installation of a gallow net, B2 class according to UNE-EN 1263:2004 [47], placed on metallic profiles anchored to the stone through resin after testing its correct clamping. Subsequently, to avoid collapse, a triple twist hexagonal metal mesh (50 × 70 mm) was placed, clamped and reinforced through lower diagonalisation of 12 mm diameter. An instrumented system of reflectors attached to previously established strategic points was installed to

control the movements of the temple (Fig. 2). The strategic points were referenced to a fixed point placed in situ inside the temple, and accurate readings took place periodically.

The installation involved placing metallic mechanised supports, firmly joined to the masonry element whose displacement was quantified by the technical team. This process was based on point coordinates (x,y,z) to calculate their spatial coordinates by the reverse three-section method [48], a geometric solution based on knowing the law of equality of angles in equal arches, and the point coordinates were included from three vertexes of known and steady coordinates. Afterwards, the foundation was improved by consolidating the ground through reinforced injection by using pipes with forming tubes with perforation of lower diameter of 76.2 mm. These works were described by Rodríguez-Mayorga et al. [45]. The auxiliary means to consolidate the first phase of column 5 are described based on several actions: stabilisation of the sheath of the column by making a 15 cm thick reinforced base by installing the corresponding anchorage plaques. For the horizontal treatment of columns, a sheath system for the column was used, coupling it by pouring plaster. In order not to damage the stone and facilitate the removal, QUIMIFLOR 25 Q, a stone sealant, was used. The metallic sheath was composed by a 3 mm thick curved sheet. Once the foundation of pillar 5 was consolidated, and the treatment of the horizontal perforations in its first 6 m was carried out, the reinforcement was placed in the areas where the triple twist mesh was installed, and the reinforcement where the support collar was fixed. All these actions required a reasonable time to study the work planning. To consolidate the structure, a support system was designed to surround and free the column from its load to conduct the safety works for all operators taking

part in the process. This support system presents a hydraulic central to load through hydraulic jacks. The column was surrounded by a metallic strengthening hoop at 6 m height. The key step to consolidate the column was the concrete grout injection with the sleeve port pipe as the repairing technique. This was a consolidation phase through reverse cement injection in which the ornamental elements of the roof were dismantled. The strengthening hoop was placed at 9 m height. The sub-vertical treatment of the pillar was carried out in two phases, a first regeneration to ensure its stability, and a subsequent definitive strengthening. The core was drilled, and, at the same time, the first reverse injection was conducted to strengthen the column to be later treated and reinforced. Afterwards, the core created with micro-concrete was again perforated, and an inclinometer pipe was placed to control movements and deviations of the columns in the future. The column was treated by drilling and fitting a high elastic limit forming tube (commonly used in the oil industry), equipped by manchette valves. In this system, the injection ends when the volume established in the project is reached or the pressures are maintained. Otherwise, the grout could be passing by discontinuities and filling gaps in domes, roof voids, among others. After carrying out the injection, a 25 mm corrugated bar (type *Gewi*), i.e., a high-quality bar joined by forming tubes, was introduced. However, if the geophysics tests performed in the column after the treatment are compared with the initial ones and yield different data from that of the first column, two other treatments would be required: the injection of resins and a radial horizontal reinforcement with stainless steel reinforcing bars to counteract the Poisson effect. In this intervention, satisfactory results were obtained, although the horizontal regeneration treatment was reinforced with shutters in the first five

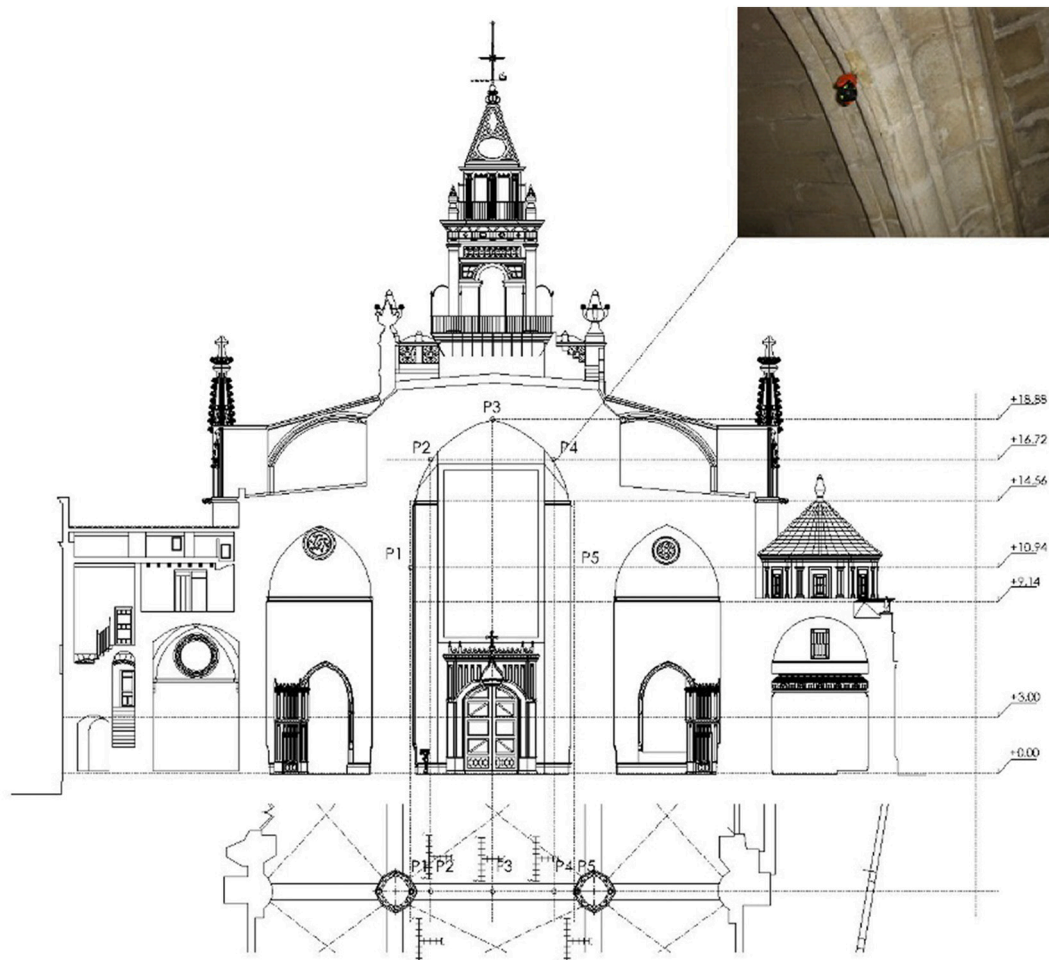


Fig. 2. Distribution of corner reflectors.

plans where it had been conducted.

3. Proposed approach

The state-of-the-art (Section 1) and the historic framework about the selected case study (Section 2) supported the organisation of the proposed systematic approach to generate a Historical Building Information Model (HBIM) for this architectural restoration project. The knowledge and intervention processes can be streamlined by structuring a digital environment able to fulfil the objectives of each process and based on this systematic approach (Fig. 3), validated in the pillar number 5 of the Santiago Church in Jerez de la Frontera. This methodology has laid the foundations for an efficient procedure that takes into account the aspects of access to historical data, maintenance, and conservation of the pillar. Exact replicas are not possible in the field of restoration since the interventions depend on the decisions of architects and engineers for, in this case, each pillar. The entire approach is divided into two main parallel environments: 1) the project environment comprising the study of the as-is condition of the architectural heritage asset and previous interventions through *Analysis phase*, *Project level* and *Construction stage*, and 2) the *Modelling environment* to manage the information acquired and defined in the Project environment within an up-to-date HBIM model created from 3D reality-data capture. The Project environment comprises the *Data processing* outputs, the *Historical summary*, the *Analysis*, and the *Evaluation* phases. The Data processing phase consists in capturing the point cloud, and performing semantic classification and HBIM. In this paper, the digital survey equipment used included: (i) traditional topographic measurement techniques, such as the laser metre and the tape metre; (ii) TLS and total station; and (iii) photogrammetry using a reflex camera [49]. In this manner, the entire investigation area was covered, thus avoiding lack of data in the acquisition. In particular, the TLS device permitted the accurate acquisition of geometry, calibrated and scaled with control points recorded using pieces of equipment (i) and (ii); an integrated high-resolution camera enabled colour mapping onto the point clouds through HDR images. A parallel activity was the semantic classification of the heritage components into architectural typologies dated to a specific period. The semantics were identified to divide objects into elements, the structure

to build the topological relationships among them, and the representation of geometries of each separated object. The next phase aimed at the Heritage construction information modelling. This phase is propaedeutic for the Modelling environment, as its output is the three-dimensional model—point cloud and mesh—to be later converted into a parametric BIM of the architectural element and become its accurate DT. The TLS data were processed to obtain the global point cloud, subsequently segmented into morphological units according to the semantic classification of the heritage components into elements via ad-hoc class-tree defined by an expert based on geometry, morphology, material, and previous interventions. The modelling process could sometimes be a tedious work because objects and shapes are uncommon. For this reason, the proposed workflow for BIM involves the use of a complex mesh obtained from the point cloud using modelling software such as Rhino or Meshlab. This is possible due to the interoperability with the BIM platform that converts the mesh into a parametric element. The accurate parameterisation of CH construction elements with complex geometries such as floral decorations, organic forms, and mythological sculptures from the history of the building, is something of a challenge for the scientific community. However, semantic models in an HBIM project do not emerge just from the parametric elements from the library, such as the case of a 15th-century late-Gothic church. Each detail is customised to fit the geometric properties of the historic building. In this study, two alternative methods were tested to select the one yielding more accurate results. In particular, the first parametric modelling approach uses the adaptive meshing techniques in Graphisoft ArchiCAD; the second alternative takes place in Autodesk Revit, where customised parametric objects (families) are created from the mesh using an algorithm developed in Visual Programming Language within Autodesk Dynamo. Once the parametric models have been obtained, it is worth evaluation the quality of the reconstruction using CloudCompare C2M (from cloud to model). Next, the execution units should be established for the HBIM by inserting all the restoration information and enriching the model semantically. With this structure, the definitions of restoration actions are being developed in a BIM environment and defining the maintenance programme in this structure.

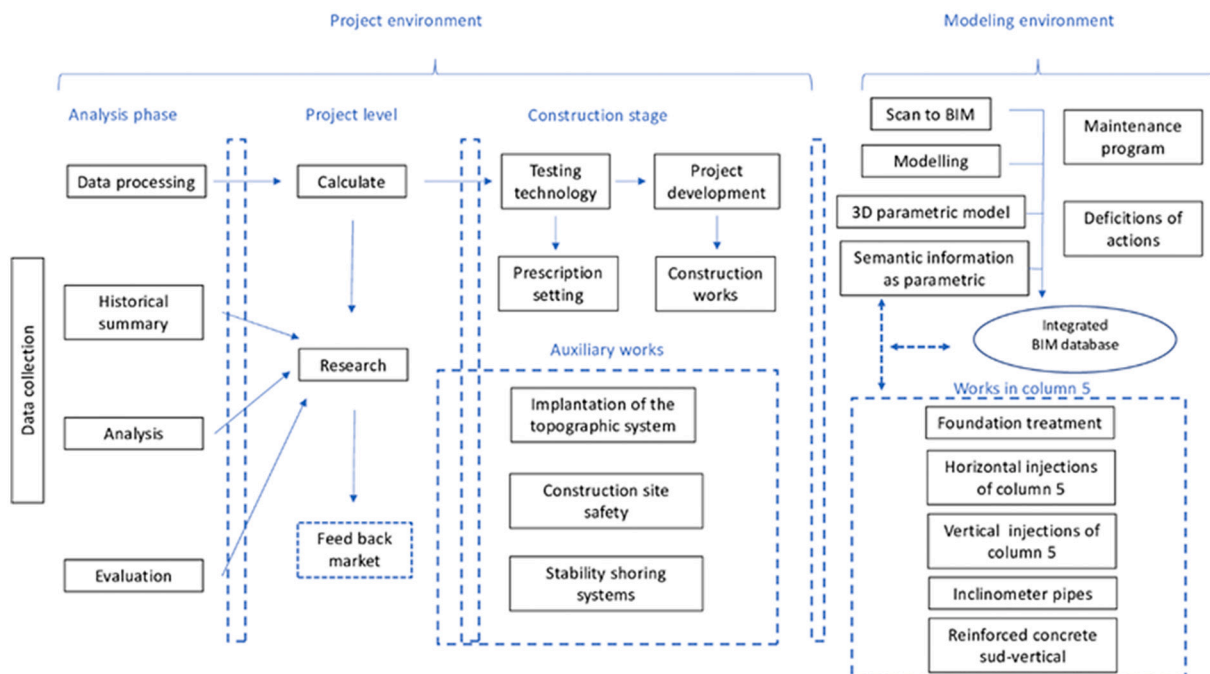


Fig. 3. Workflow of the intervention phases.

4. Data processing

4.1. Capturing the point cloud

Numerous current works focus on capturing point clouds for the 3D reconstruction of immovable heritage assets [50–54]. Thus, architectural and archaeological heritage should be documented using the new Massive Data Capture Systems (MDCSs). Using image capture techniques or laser scanning is a daily challenge to study and analyse heritage. In general, the three survey methods mentioned in Section 3 (i, ii, and iii) are used for suitable documentation and recording. The area chosen in Santiago Church is column number 5, which is in the Epistle Nave. Three scan locations were set to cover the 360° of the column to record point subsets of the foundation, base, shaft, capitals, and arches. The whole area to be studied was covered by this procedure. Measurement was conducted using a Leica ScanStation C10 laser scanner, reaching 120 m for geometry capture, and an integrated camera of 4 megapixel was used to map colours onto the point cloud data. The high-speed pulse laser scanner determined the mean distance through the Time of Flight (ToF) technology with the specifications indicated by Pukanská, K. [55]. However, given its greater resolution, the NCTech Istar camera was used to obtain HDR images to map the colours onto the TLS data. According to the manufacturer's information, the Leica Flexline TS02 total station with an accuracy of 2 mm [56] was used to record the control points. The range clouds were processed using Leica Geosystems Cyclone software.

4.2. Semantic classification

From the architectural analysis point of view, the semantic classification is important due to the many architectural typologies existing in various historical periods [19]. The same object could have various names, materials, or construction techniques. A semantic platform from the building morphology point of view could have three levels [57]: semantic, structure, and a representation level. The semantic level allows shape objects to be separated; the structure level allows the elements to be organised; and the third level enables the geometric representation of each separated object. To segment a column from the geometric construction perspective, the semantic description of the morphology in its different parts should be considered: the plinth as a settling element of the main structure, the decorative base in the column, the shaft, and vault arches. When developing the model, these conceptual entities should be segmented according to their geometric shapes. The selection procedure does not distinguish materials, so the morphological units are usually composed by various materials and are considered valid for a 3D structure. This definition would be appropriate to reach a LOD 300. The subdivision guarantees that the construction model generally presents geometric properties of a DT. However, the semantic classification should also be studied [58]. Selection mechanisms generally focus on classification studies through simple geometries, such as plans, cylinders and spheres. Diverse studies address this issue, taking the point cloud from SfM [59–61] or TLS [62,63] as reference.

4.3. Heritage construction information modelling

Three-dimensional architectural objects have been created since the advent of the digital age, an inducement to create small CH objects. Through the traditional use of CAD, in the early 1980s, graphic expression lied on vector entities with a simple representation function: 2D and 3D. This procedure was modified in the 1990s with the emergence of software that aimed to represent or model buildings semantically. This type of software was called BIM at the beginning of the new century. An example is Graphisoft ArchiCAD, an architectural programme that uses an advanced technology supported by the Geometric Descriptive Language (GDL) programming. This innovative software has

met AEC industry users' requirements by modelling various parametric objects in an intelligent and comfortable way.

To model new buildings, manufacturers provide technical teams with new construction components to be used by the operators of BIM digital platforms. These operators are useful to generate the building model in certain LOD levels. However, CH architectural elements have singular geometric and physical characteristics. Thus, to accurately model GDL, the process in CH should start by remotely compiling topographic data through TLS or SfM to create DTs. Although there are studies based on the digital workflow to model complex structures in BIM [64], procedures are still very complex. In previous research studies [7], the GDL programming language solved the problem of the data exchange file format to create parametric objects. GDL allows dimensional, physical, and environment properties to be manipulated and adapted to the characteristics of the building. Another advance arises when historical models remain difficult to automate without a fully effective methodology, which constitutes a knowledge gap in the 3D reconstruction of archaeological, architectural, and artistic heritage. Even nowadays, most projects include parametric elements modelled influenced by the operator's intuition in the BIM digital platform without establishing automatic procedures. This way of working allows primitive geometries to be used from plans, drawings or the point cloud included in the BIM project; however, other rapid visual programming procedures use applications that reinforce and facilitate modelling in the BIM platform such as Dynamo and Revit, or Grasshopper+Rhino and ArchiCAD. These new workflows graphically introduce the programming language in modelling. A very recent example is a stone pavement road located in the Archaeological Site of Pompeii [65]. In this regard, ArchiCAD 25 includes a GDL visual programming with PARAM-O, available for Windows and macOS [66]. Customised parametric library objects and construction elements are created in a quick and simple way without including any code line or GDL script. Similarly, the new connection with Python allows scripts to be executed to automate processes by providing accuracy, thus enriching the workflow in the BIM project environment [67].

The problem arises when digital modelling software, which are commonly used for contemporary construction projects, are required to create complex geometries accurately but without an established or referential order. Most BIM solutions are not appropriate to handle complex designs natively [35], particularly when the designs are unique pieces to be protected that include singular features or are affected by the transposition of techniques throughout their historical development. A family is a group of elements with a common set of parameters and graphic representation [68]. The parametric model of column 5 of the Santiago Church in Jerez de la Frontera was created using the families of the Revit system, thus allowing to work with components from the software library to model simple surfaces. Afterwards, these families facilitated interoperability by exporting the customised components of the entities to a file.

The modelling process could sometimes be a tedious work because objects and shapes are uncommon. This type of software should be very intuitive when working with walls, concrete columns, metallic columns, and slabs, among others. Today, they focus on daily elements that are used to construct new buildings. These elements are parameterised in the various programmes used, although they may have very different, even unusual shapes. However, the design of complex architectural elements is a more complicated issue; these elements could involve ornamental elements supporting them. When creating a complex geometry in Autodesk Revit, geometries should be analysed, thus turning them into simple geometries. In the case study, column 5 was divided into several geometries grouped based on their semantic features. The process first consisted in processing the point cloud in .e57 format in Autodesk ReCap software to make it compatible with the point cloud file in Revit (see Fig. 3). Once the point cloud was imported into Revit, five levels were created; this significantly changed the column geometry. Fig. 4 shows the segmented geometry of the column model based on the

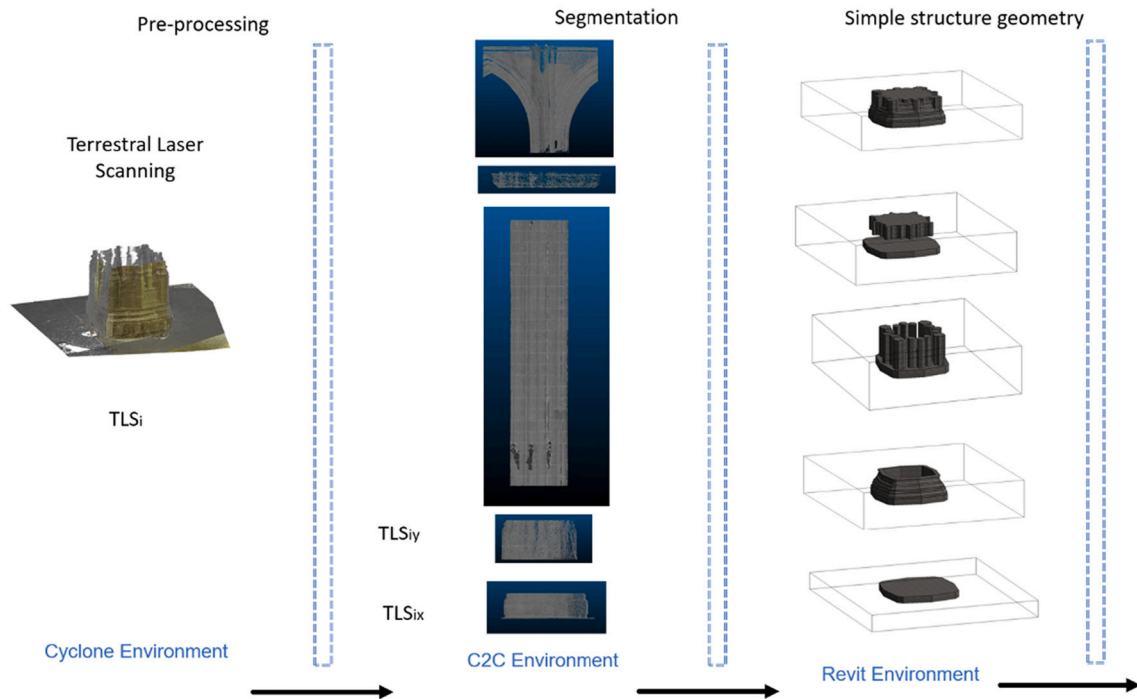


Fig. 4. Workflow of the modelling phases.

structure proposed according to an ad-hoc semantic classification defined based on restoration expertise. The segmentation scheme units were structured from the TLS global point cloud to segmented morphological units, considering the most optimal geometric construction process (TLS_{ix}, TLS_{iy}) in the general set. (see Fig. 5.)

The following workflow involved the transition from the point cloud to a complex mesh using a digital modelling programme such as Rhino or Meshlab. These units of complex meshes were exported to the BIM digital platform through a conversion operation between the mesh and the parametric element. Adaptive meshing techniques were used, and practical interoperability was implemented. The workflow of the adaptive meshing in ArchiCAD is complex:

- i) Manual or automatic segmentation of the point cloud in subsets with semantic content, i.e., choosing parts by an adjustment selection of models in a particular meshing software, and next treated in the BIM environment;
- ii) transfer of the complex mesh geometry to the BIM software by an interoperability process of the elements using one of the several openBIM formats, such as IFC (.ifc), IFCXML (.ifcxml), and IFCzip, and native files such as .3ds (3DStudio), .3 dm (Rhino), .Skp (SketchUp) or stereolithography formats (.stl).

This mesh should have enough geometric accuracy to be used as a replica of the actual component. The most used way to convert the point cloud into a mesh is through software packages such as MeshLab, Rhinoceros, CloudCompare [69] or Agisoft Metashape programme [60]. If C2C is used, Rhino can also be used to export to .3DS format, which is a simple procedure. Converting the point cloud with a non-structured format, such as .e57, into a mesh is more complex in Rhino, but it is widely used because this software has been selected by its popularity as a platform to edit and create geometries [35]. Metashape allows point cloud files from the TLS to be recovered, which makes it an interesting tool to generate lighter meshes against other programmes. Therefore, it is worth highlighting the operability of this process given the wide export options of formats; iii) after obtaining the mesh, it is automatically adapted to a GDL object and included in the ArchiCAD library. The complex part of this step is rotating the objects so that the mesh surface is in the XY plane; iv) the GDL objects should be transformed into a *morph* element; v) after creating a regular parametric solid (Wall, Slab, Pillar, or Mesh), the surface defined by the point cloud was adapted through Boolean operations to that parametric element. The actual shapes of the segmented objects were used as division surfaces (subtraction with extrusion upwards Boolean operation in ArchiCAD). As Fig. 7 shows, this workflow was used by Nieto et al. [70] to manage the distorted geometry of the Pavilion of Charles V of the Real Alcazar of Seville in an HBIM project and to exchange correct information among the experts involved in the conservation of the historic building. This work encourages the creation of an as-built HBIM with detailed structural deformations created from TLS point clouds. Moyano et al. [70]

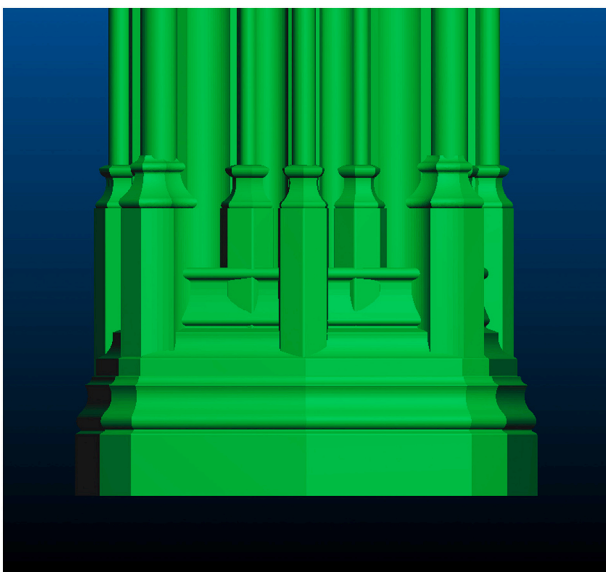


Fig. 5. Ideal model of column 5 generated from segmentation.

also used this workflow in the primitive solid volumes of the walls of a megalithic monument of the Copper Age. The workflow to establish parametric models generated from an adaptive mesh (AM) is a process developed in two environments: CloudCompare and ArchiCAD. Fig. 6 shows a model that includes the process described.

As mentioned above, the transition from mesh to BIM requires significant efforts. This fact has been recently showed. To model a church, Constantino et al. [27] worked with point clouds in Rhino 7 and Arena 4D to generate the model through Boolean operations, extrusions, and lofts. This process requires very solid and rapid hardware, although the authors indicated that they obtained a parameterised model with which a material could be associated.

Another interesting study into the transformation of meshes into BIM objects is that by Yang et al. [71]. The workflow leads to obtaining a mesh from TLS data or SfM in low-density meshes [72], converting the holistic mesh into NURBS using Rhino and then using the Revit Dynamo package. Finally, a parametric object with the geometric properties of the shape of a complex element can be obtained, and therefore its structure cannot be modified in BIM. There is a Mesh Tool Kit for Dynamo on the market [73], which describes the transformation of the point cloud to a Revit model. In this sense, the modelling of door and window frames with an organic and geometric geometry consists of various workflows through CloudCompare, Recap, and MeshLab to obtain a mesh exported to .dxf in Revit. The parametric model presented as a complex shape aims to simplify by modelling the Revit family file through rigid relationships. According to the authors, the model accepts variations of the wall thickness or the width and height of the frames by simplifying forms, so the true DT is not reproduced. Thus, the challenge when using Revit is including a complex holistic mesh in the software itself. In this regard, there are various software packages speeding up the process. For instance, Convert a mesh [74] is a Rhino plug-in that transforms the mesh directly into Revit families. The same section establishes the limitations of the workflow: i) the meshes imported cannot obtain the materials assigned, and ii) users should use visibility graphic overrides or object styles to control the graphs of the mesh imported. Another proprietary application is Mesh import from OBJ files [75], an add-in of Autodesk Revit. However, it has certain limitations in the size of the mesh and several aspects of the OBJ format, e.g., the smoothness is not exported.

A Rhino model can also be imported directly to ArchiCAD and turned first into a non-editable GDL object maintaining the logic structure of the original Rhino model. It is placed in the embedded library of the BIM project, but the segmentation of the model can be adjusted before or after the import, according to the definitions of smoothness of a curve object. Nevertheless, a great amount of polygons has an impact on both the file size and the hardware performance.

The second alternative for BIM parameterisation of the mesh of column 5 (.obj format from Rhino) is based on the use of VPL in Autodesk Dynamo. The mesh nodes were detected through meshtoRevitElement.dyn, a code package. For this process, the mesh triangles were reduced, and the element was created in Revit by determining the family and the material. Fig. 7 shows the Dynamo code.

4.4. Evaluation of the model quality for the heritage reconstruction

The (TLS_i) global point cloud includes sectors that are not required to evaluate the model. The aim is therefore to segment the points that do not represent the sample. One of the elements identified is the floor. For that purpose, CloudCompare, a widely used open-code programme [32,49,76] was used. TLS_n was considered as a referential auxiliary to produce the model under the Mesh to BIM (MBIM_n) approach using Revit software. Nieto et al. [77] showed that including point cloud data in the BIM software (ArchiCAD and Revit) is essential to compare geometric measurements against traditional techniques. Dynamo was used to assess the quality of the model built and to analyse the structural deviations between the parametric model and the actual geometry, for which the data were converted into an .xls file. To assess the potential of the method used, structural deviations were measured using the parametric model in .stl format and the point cloud in .e57 with C2C. This dataset showed the capacity of both the aforementioned techniques and the BIM parametric models to analyse structural deviations. At first, the model of the column was structured in three point clouds in .ptx format from the postprocessing. That was the result of TLS_n. Evaluating the quality of the model should be the first step. For this purpose, this research used the closest point algorithm that recalculated the transformation parameters for the distance of the homologous points. The maximum estimate of the roto-translation between TLS and Model to BIM is obtained by reducing Eq. (1) [78].

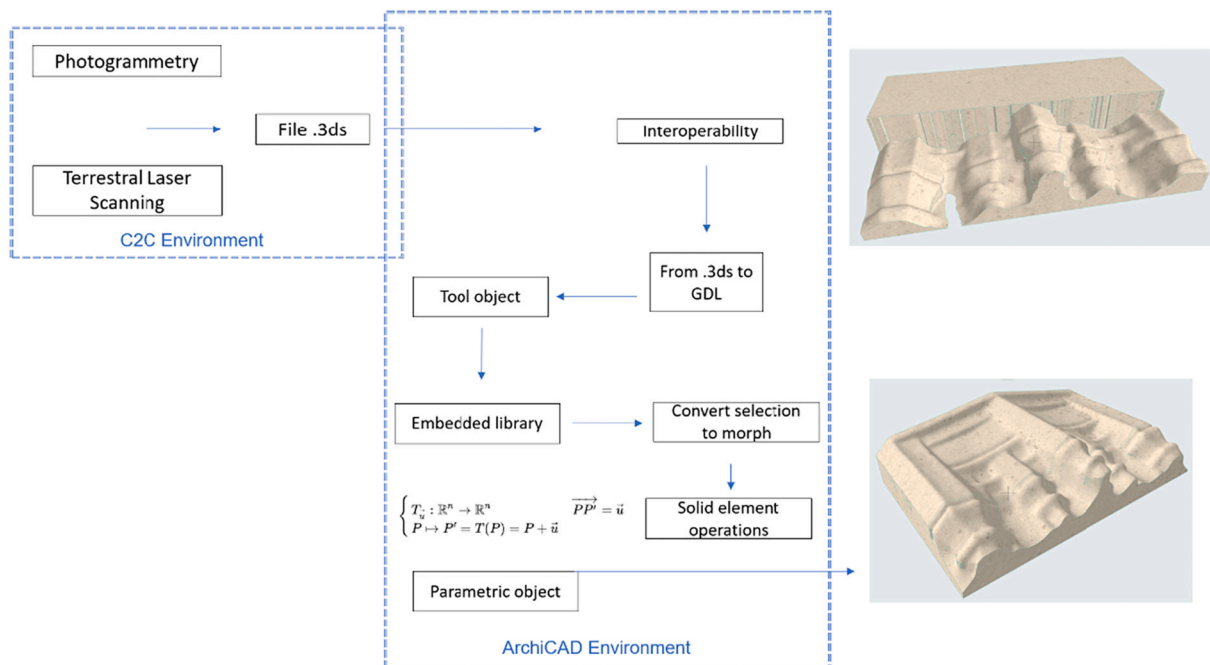


Fig. 6. Parametric model generated from an AM in ArchiCAD.

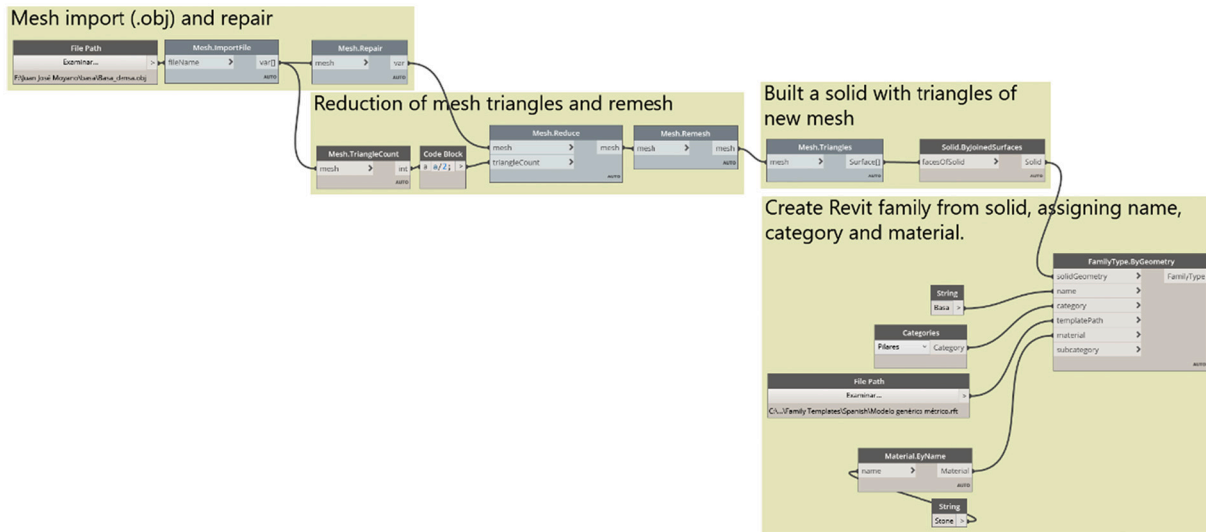


Fig. 7. Creation of BIM objects of complex elements by using the NURBS surface turned into specific BIM families.

$$\sum_{i=1}^N \|(TLS_n - MBIM_n)\|^2 \tag{1}$$

4.4.1. Evaluation of the ideal model

After obtaining the TLS_n point subset of the whole column (survey 1), the HBIM construction model was aligned to the subset sample of Fig. 9 through common points selected between the .stl model and the point cloud in .e57 format. The 6 pairs of points were obtained in the base of both the plinth and the pillar. The record was applied with the Iterative Closest Point (ICP) algorithm implemented by CloudCompare M3C2 and created by Lague et al. [79] to automatically optimise the alignment. The algorithm yielded a standard deviation with an RMS of adjustment of 0.07237 m.

After the roto-translation, the TLS point cloud was aligned to the model of the whole column generated in BIM in which the differences between the two geometric models could be evaluated. Evaluating the quality of the construction with BIM is among the challenging tasks for professionals, lecturers, and researchers [80]. This is a critical point to determine the construction in BIM. This evaluation should be established by C2C, providing the results of Figs. 1 and 2 and obtaining the following values (Table 1).

The distance between the model and the segmented pointset of the portico was calculated (Fig. 8 a) and b)). The parameters studied were the Root Mean Square Error (RMSE), the minimum and maximum distances between the model and the point cloud, the average distance, the standard deviation, and the estimated error in metres, according to Eq. (2). The deviation between the DT model and the actual geometry presented two characteristics: as indicated by Antón et al. [32], the high presence of points in Value 0 (Fig. 8 b)) in comparison with the other distance intervals; also, the high standard deviation that can be calculated through Eq. (2):

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\Delta X_i)^2 + (\Delta Y_i)^2 + (\Delta Z_i)^2}{n - 1}} \tag{2}$$

Where:

- o ΔX ; ΔY ; ΔZ are the differences between the coordinates of the point cloud and the coordinates of the closest points of the 3D model.
- o “N” is the number of control points.

The lowest part of the column, including the plinth, was next segmented. Both the parametric model and the TLS point cloud behaved similarly, and the point difference was obtained Fig. 9.

4.4.2. Evaluation of the parametric twin

The parametric DT was obtained in ArchiCAD through an adaptive mesh (Fig. 6) by following the workflow involving CloudCompare and the BIM software. However, to obtain a 3D model as a parametric twin element in Revit, the process adopted a workflow already started by Constantino et al. [27] but in a very simplified way. Although Grasshopper and Rhinoceros were used to achieve an implementation in Revit, a workflow based on multiple point cloud profiles was also followed to construct parametric elements.

Experimentation was reached by simplifying the meshes using Rhino V7 with Quad Remesh (Fig. 10). Simplification and NURBS generation were enough to achieve parameterisation in Revit. This simplifies the workflow, as Fig. 11 shows. Thus, after obtaining the point subset of the lower part of the column, the .stl format exported to Revit was obtained. According to Eq. (1), the comparison was performed through a roto-translation between the TLS_{iy} subset and the Quad Remesh exported to .stl through common selected points. Survey 2 included the analysis of the 6 pairs of points obtained both in the base of the plinth and the pillar. The record was applied with the Iterative Closest Point (ICP) algorithm implemented by CloudCompare M3C2 and created by Lague et al. [79] to automatically optimise the alignment. After applying that algorithm, the software yielded a standard deviation with an RMS of adjustment of 0.01402 m.

After the roto-translation, the TLS_{iy} point cloud was aligned with the model generated in BIM. Here, the differences between the two geometric models could be evaluated using C2C. The results of this evaluation are shown in Figs. 1 and 2, and Table 2.

The distance between the model and the segmented pointset of the portico was calculated (Fig. 11 a) and b)). The parameters studied were

Table 1
Data from the comparative study between TLS and whole column.

Experimental surveys	Standard deviation (m) (σ)	RMS (m)	Min. distance (m)	Max. distance (m)	Average distance (m)	Estimated standard error (m)	RMS adjustment (m)
Survey 1	0.0536	0.0534	0	0.3718	0.0191	0.0831	0.07502

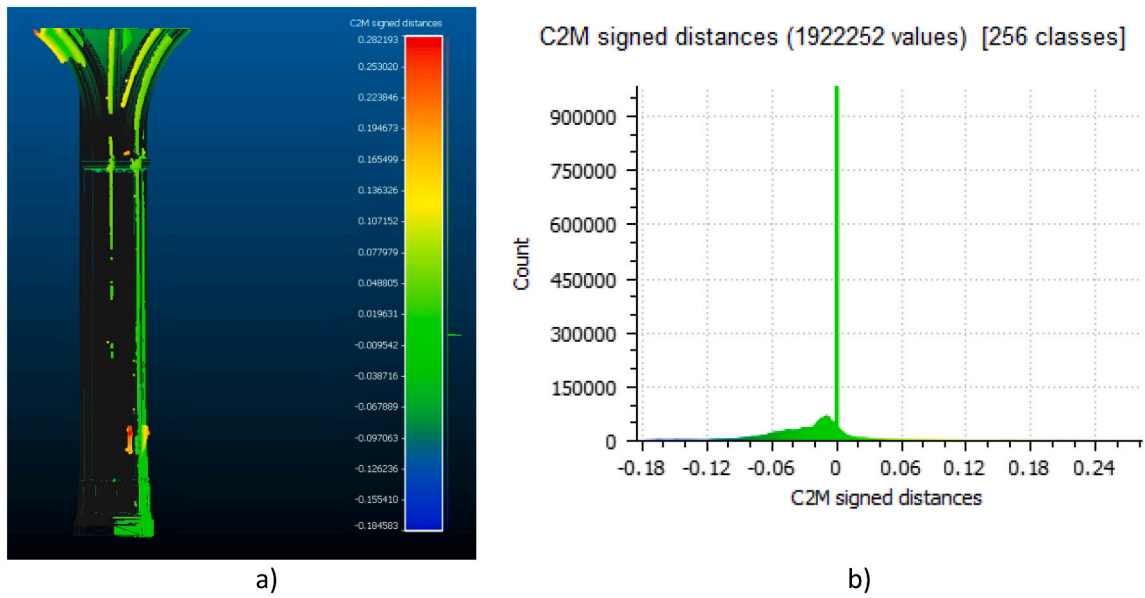


Fig. 8. a) Parametric model of column 5 generated from the segmentation of the point cloud. b) Histogram. Units: metres (X-axis) and number of points (Y-axis).

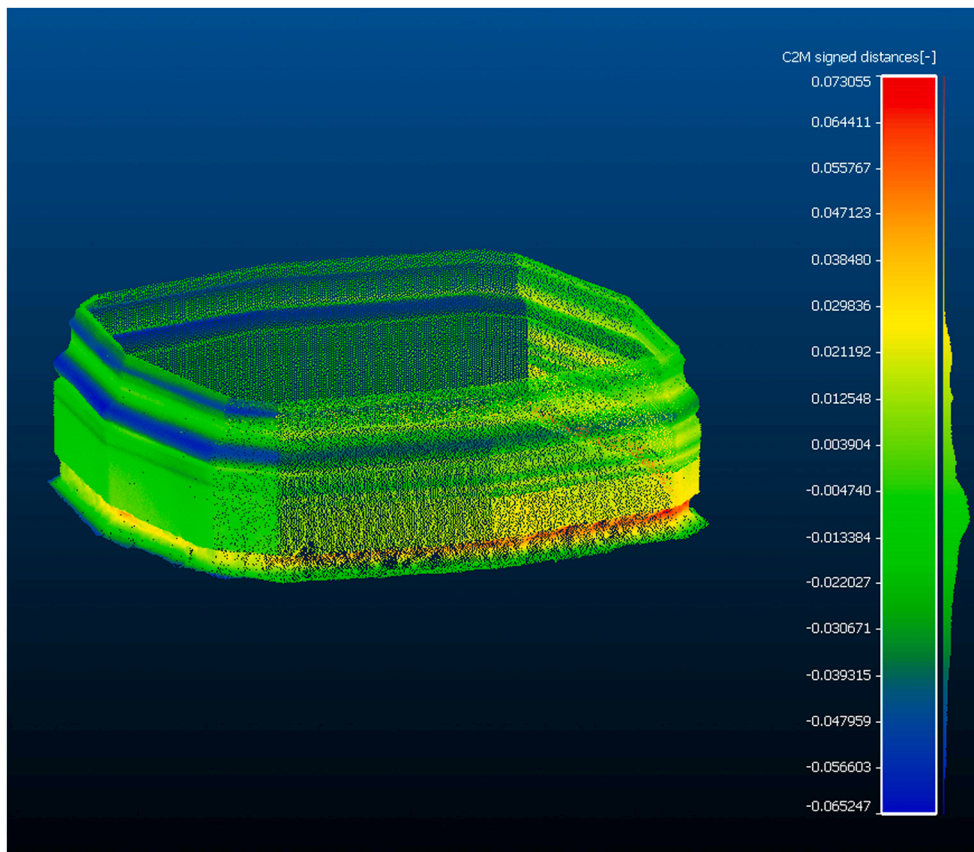


Fig. 9. Parametric model of column 5 generated by the segmentation of the point cloud.

the Root Mean Square Error (RMSE), the minimum and maximum distances between the model and the point cloud, the average distance, the standard deviation, and the estimated error, according to Eq. (2).

5. Model management

5.1. Ontology use

One of the main advantages of digital BIM platforms is the possibility of transferring information content to graphic representation units in structural and architectural sites. Coordinated information must be

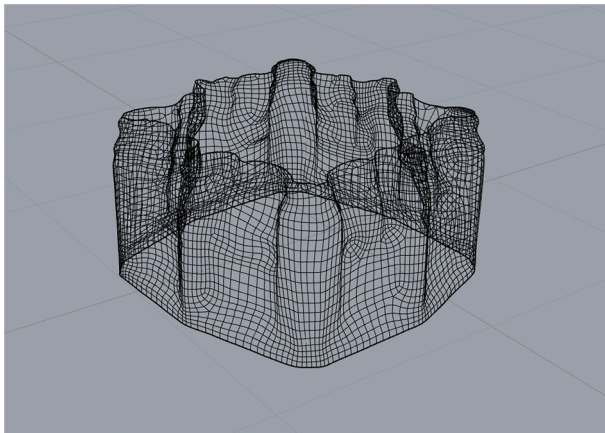


Fig. 10. 3D model generated by simplifying Quadmesh in Rhino V7.

transmitted among operators to find new paths to improve product quality. In this regard, BIM platforms enable operations within the same software, such as TeamWork-HBIM in ArchiCAD [81]. An ontology defines a common vocabulary for operators or researchers that need to share information within a domain. Thus, ontology in BIM is an analysis method of semi-structured information used to acquire knowledge and communication among people, representing the interactions among BIM users through attributes, concepts and relations [82]. Ontologies applied to BIM convey or carry part of the knowledge between the operators and the technical teams taking part in restoration. Operators should recognise the ontologies and define levels of semantic data integration to contribute to users' dynamic communication. The case study in this research was based on associating semantic information with the activities carried out various stages of the restoration process of the column of the Santiago Church. Each component represented non-geometric aspects, including construction characteristics, execution date, and material properties. Semantic implementation enriched the 3D representation by adding information stored, formalised and verified in the knowledge base of the activities of the heritage process [83]. Semantic implementation is not new in relation to CH. Messaoudi et al. [84] and Acierno et al. [83] worked on this issue with Revit BIM through

Protegé, an open database software.

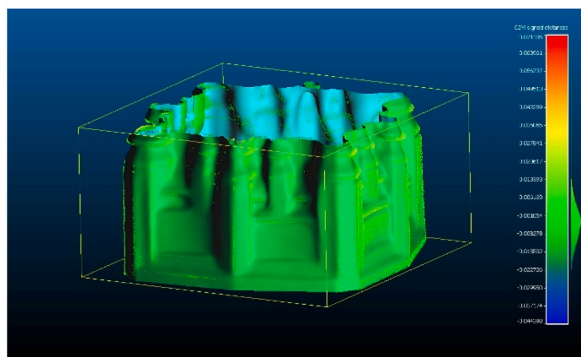
One of the goals was to transfer the information obtained from the execution phase when restoring column 5 into an information model to be created. Thus, the various interventions by the technical teams could be recorded, and such teams would be able to interact. Fig. 12 represents the vertical connectors through longitudinal injections from the base to the upper part of the column. Fig. 13 represents horizontal injections.

5.2. Use of open standards for information transfer

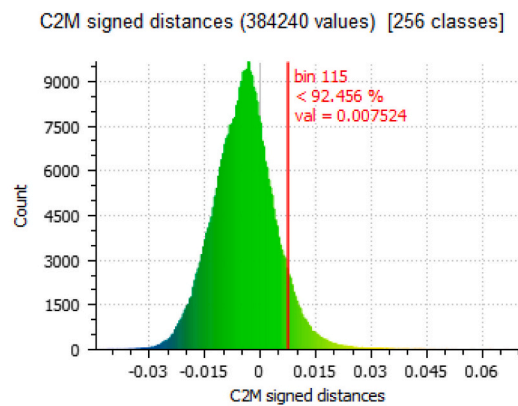
The use of the BIM methodology through open standards, the so-called OpenBIM, should be encouraged, thus strengthening the interoperability among agents, processes, and tools. The creation of a BIM for remodelling or renovation purposes based on IFC implies what is defined by Scherer and Katranuschkov [85] as BIMification, a process that goes through two stages. The first stage is anamnesis, dedicated to the survey and collection of facts about the building; and second is the diagnosis, the analysis and interpretation of the needed facts collected. The use of common standards and internationally agreed by all agents from the AECO sector is crucial to increase the benefits of the BIM methodology. The IFC ISO 16739 [86] (Industry Foundation Classes) works as a container of information that eases the exchange of a BIM information without losing or distorting data. The IFC format is therefore neutral to facilitate the interoperability among several specialists that use various software. The structure of the IFC file consists of entities such as construction, geometric and basic elements, and the BIM software turns the file first into layers and, secondly, into parameters. BIM platforms export building elements to an IFC file. In Revit, it is established according to the categories or subcategories of such elements. When creating subcategories, the IFC to which the elements of a family belong should be specified. The last goal of this study was to have an IFC data container to represent the column, using the *IfcColumn* specification as the most appropriate semantic definition, thus establishing starting limitations to geometrically represent all the elements of the column and the provision of the use of materials, parameters, and systems used in the restoration.

5.3. Building classification for HBIM

One of the goals is providing the heritage sector with a standardised



a)



b)

Fig. 11. a) Analysis of the construction model and the point cloud of the base of the pillar. b) Histogram. Units: meters (X-axis) and number of points (Y-axis).

Table 2
Data from the comparative study between the TLS_{iv} data and the parametric model.

Experimental surveys	Standard deviation (m) σ	RMS (m)	Min. distance (m)	Max. distance (m)	Average distance (m)	Estimated standard error (m)	RMS adjustment (m)
Survey 2	0.0074	0.0073	0	0.0671	0.0496	0.0075	0.01402

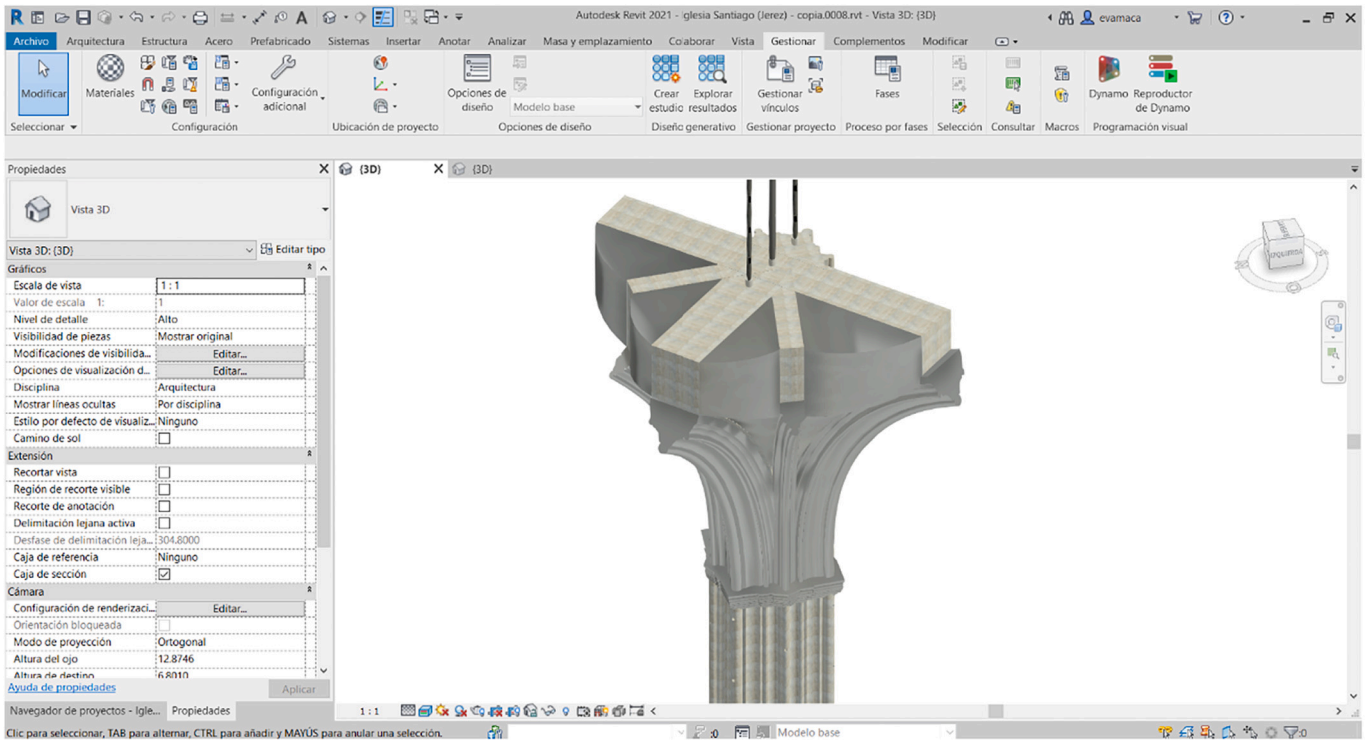


Fig. 12. 3D-construction model.

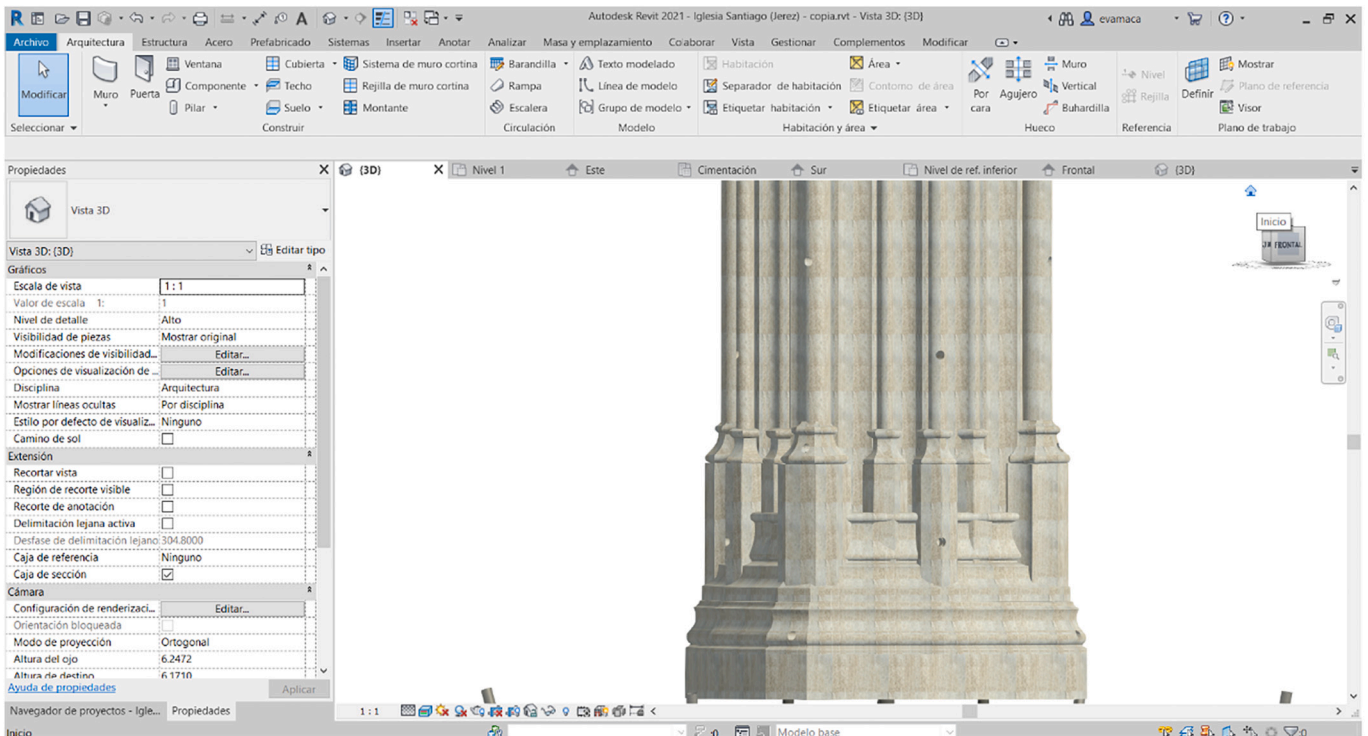


Fig. 13. Identification of horizontal micro-concrete injections.

terminology and semantics. There is a need for using classification systems in the HBIM context. The aim of ISO 12006-2 is to ease the comparison of the standards definitions for the systems of various countries [87]. Using a classification system allows the model to be structured by a known basis to be shared among agents. More and more countries are establishing their own classification system, as BIM Content packages

[88] show.

A widely acknowledged system is Uniformat, from the US and Canada [89], which standardises the nomenclature of all the building elements [90]. The ASTM E1557 standard (Standard Classification for Building Elements and Related Sitework- UNIFORMAT II) provides a common structure in which the construction programme, specifications,

and estimates are bound together. Including this standard in the design improves the communications and coordination among all participants in the projects, thus enabling a quick design, and an important increase of productivity. There is a parameter for this code called Assembly Code (AC) that requires an integrated process modified by the user. Work Breakdown Structure (WBS) is a centralised database and the foundation of construction project management [91]. It could be used as a record management element. Uniformat provides a hierarchical order through levels, composed by the elements of the project. This structure is organised in five levels: A, A10, A1010, A1010.10, and A1010.10.CF.

Since 2017, GuBIMClass, a classification system, has been established in Spain [92]. Its goal is to create a classification system fulfilling the needs of the Spanish sector. It is mainly based on guaranteeing the traceability throughout the life cycle of the building, the homogeneity of the site, and the language of the system. The code is structured in 9 levels: CD, 20, 20.20, 20.20.20, 20.20.20.10, and so on.

Moreover, Omniclass [93] was developed by the Construction Specifications Institute in USA. This is an organisation and classification system based on a classification of codes organised in various tables according to their function and shape, among other aspects. It is made up of 15 tables representing each part and property of the construction, from construction entities by function to products, including elements. The levels of the code are 21-01 00 00, 21-01 10, 21-01 10 20, and so on. These classification systems are included in the structure of the IFC file to specify the system, whether a public standard or the adaptation of any other system of a company. In architectural or historical heritage there is no standard, considering that it is also a part of the facility maintenance. This aspect should therefore be studied to establish new guidelines to classify CH according to the existing codes to know the specific features of the historical building, including archaeological, architectural, and artistic features. Several studies focused on HBIM have used OmniClass for the hierarchical structure of the elements [94,95], as well as Uniformat [96], or link information assignment to each parametric component in Uniformat II [97]. The interesting aspect is that an open code can be created within the model to include the information by adding databases. The implementation of a semantic classification based on a hierarchy of classes and subclasses is useful to store the information on heritage deterioration and the characteristics of the materials of each structural part [98]. Following the line of work of Malinverni et al.[98], a class structure can be established in the heritage building by analysing the exterior and interior and dividing floor, slab, wall, pillar, arch, beam, and roof into subclasses. For this study, there would be a substructure divided into the plinth, foundation, base, shaft, and capital of the column.

For collaborative and standardised work in the AEC sector, it is mandatory to automate a classification of elements of a project to reinforce open BIM. ArchiCAD was the first software to bet on efficient interoperability between intervening agents; it continues to be the most flexible in the IFC mapping process. The ACCA Edificius platform [99] also facilitates the mapping of IFC classes based on a text file that maps the categories generated by any native BIM application. In reference to the Autodesk platform (Revit), the Omniclass classification is the only one that is clearly displayed in the element properties window. Although AC [100] is also helped to introduce Uniclass subclassification systems (although difficult to identify) or Keynote for customised and own labelling. In the latest version of Revit (2023) an Interoperability plug-in can be used to load the internationally validated classifications and assign classes and types to elements. These systems are easily used and are useful for industry and the construction sector. The applicability of these systems is still scarce in the restoration sector. Bruno and Fatiguso [101] shared information on diagnosis tests through Microsoft Access, related with Excel or SQL, in which the attributes included in the model were used as programming fields for diagnosis reports. This field should be developed in heritage buildings. The taxonomy of the data in an information model, such as the hierarchical and systematic order of the information, is crucial to be successful in a restoration project.

In this work, a classification process for an element in a historical scenario has been experimented with; a Keynote parameter was initially associated, including component and material levels. To include keynotes, the user could divide data into categories, families, types, and instances. These keynotes should be included in a .txt file (Table 3).

The legend works as a planning table that could be included in plans [102]. Keynotes work as codes to classify and describe the elements of the restoration project. In this classification, the novelty is the component of treatments that are part of the construction model (Fig. 14).

To complete the process, a standardised classification of the elements of the column 5 model is applied, trying to get closer to the construction typologies of the time and the interventions for its consolidation. The current classes and types in Omniclass, Uniformat II, Uniclass 2015 are not adapted for the historic building. Therefore, if a very generic classification is not wanted, it is necessary to create new chapters and subchapters. This is except for Omniclass, which does not allow the introduction of new codes in the Revit BIM platform, if possible, in the case of Uniclass. But the use of a personal encoding, not established by an international standardisation body, can bring about other problems of inappropriate codes or discrepancies with other similar cases. Finally, and with difficulty, the elements have been classified adjusting to the current bases, leaving for future research a more appropriate use to classify CH construction systems. Fig. 15 shows the process carried out in the classification, with the creation of a table of classified elements to be exported to IFC.

Another drawback has been that IFC mapping is not automatic when systems are very specific. This has led to a custom mapping of construction classes before being exported. Figs. 15 and 16 show the IFC data of an intervention entity (BIMvision).

To include information in the parametric model, each family represents a treatment conducted in the column. The information is established in the *identity data* section, thus representing its description, technical requirements, reports before the action or any other interesting data that is, in turn, included in the *family properties* (Fig. 17).

Another element included in the restoration of the column was the treatment using the inclinometer pipe. This record was essential to control the maintenance and possible deviations in the future; the latter could be anticipated, thus preventing collapse. Apart from the technical requirements of the material installed, the data obtained from the first clinometry of column 5 are indicated to compare them with future analysis and find possible impacts (Fig. 18 a) and b)).

The column base automatically modelled from the mesh in a Revit

Table 3
Classification included in Revit through Keynote.

CODE	DESCRIPTION	JOINT
COLUMN		
00.01.01	Floor	COLUMN
00.01.01.01	Granular sub-base	00.01.01
00.01.02	Column	COLUMN
00.01.02.01	Base	00.01.02
00.01.02.02	Shaft	00.01.02
00.01.02.03	Capital	00.01.02
00.01.03	Roof	COLUMN
00.01.03.01	Diagonal Ribs	00.01.03
00.01.03.02	Ribs	00.01.03
COLUMN TREATMENT		
00.02.01	Foundation cement treatment	COLUMN TREATMENT
00.02.02	Horizontal injections of column 5	COLUMN TREATMENT
00.02.03	Reinforced concrete sub-vertical	COLUMN TREATMENT
00.02.03.01	Reinforced concrete sub-vertical	00.02.03
00.02.03.02	INCLINOMETER PIPE	00.02.03
00.02.04	Vertical micro-cement injections	COLUMN TREATMENT
00.02.04.01	Gain	00.02.04
00.02.04.02	Injection pipe	00.02.04
00.02.04.03	Gewi corrugated bar	00.02.04

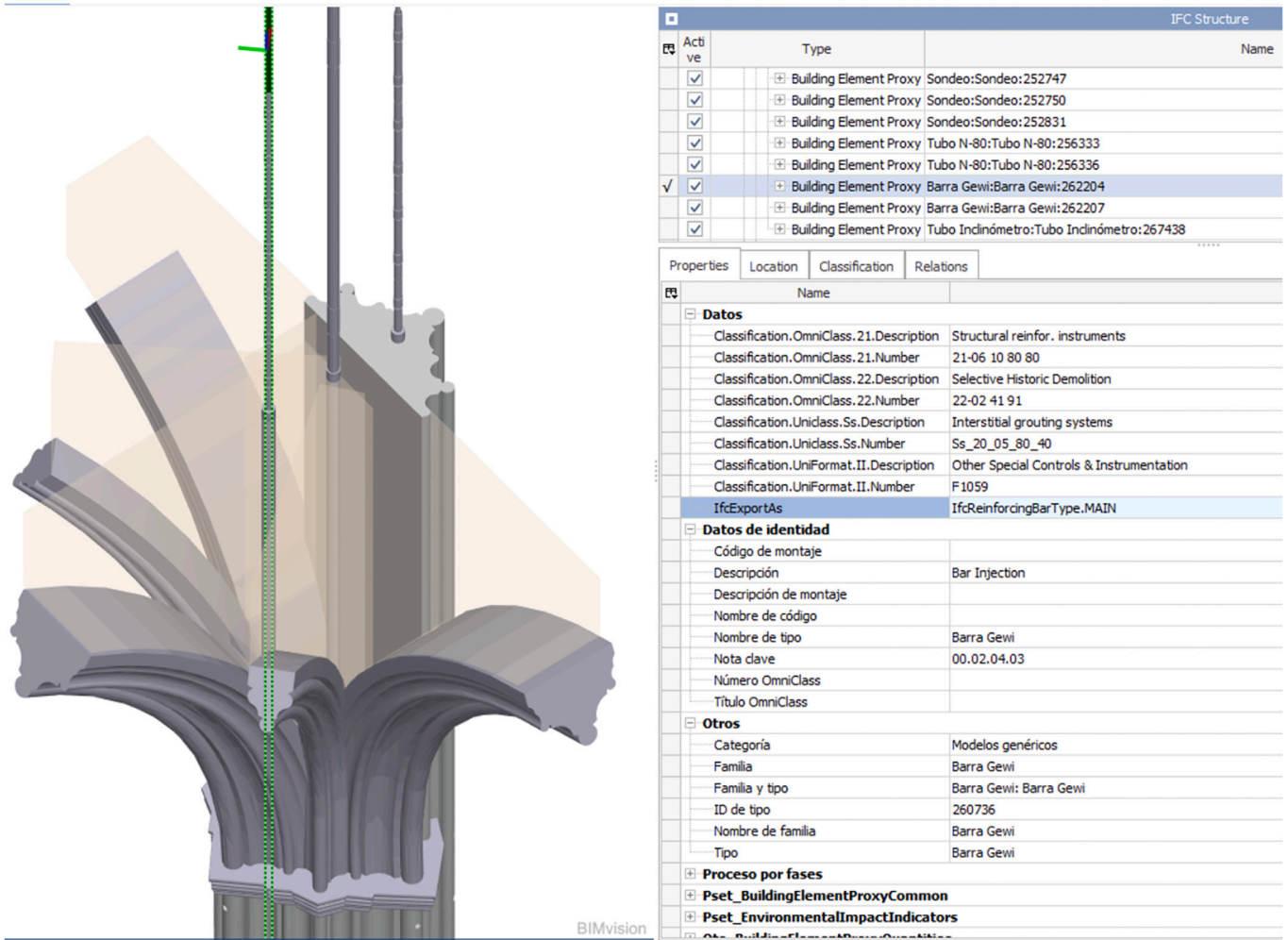


Fig. 16. Data associated with the elements (case of Bar Gewi) of the IFC model (BIMvision).

Consequently, these parameters were inserted in each element of the model (basement, inclinometer pipe, and Gewi bar, among others) as shared parameters after accurately defining the data structure and data type to be easily understandable by technicians and readable by openIFC viewers. In this sense, the BIM of the base (carried out from the automatic generation of the mesh) was exported in IFCx4 Reference View, including IFC and custom parameters to be widely navigated using IFC viewers such as BIMvision (Fig. 20), Open IFC Viewer, and Solibri Anywhere. As evidenced, the use of images as properties in Revit does not permit to consult them in the IFC viewer as the images in .jpeg and .tiff formats, among others, are not IFC data types. This leads to provide reports and pictures within the working group as a URL from shared folders (a common or on-line server such as Google Drive or WeTransfer). In addition, the introduction of the parameter 'Sonic tests (P-waves velocity)' with data type 'speed [m/s]' within the IfcColumn (building element) causes the loss of the reference measure unit in the IFC viewer because 'speed' is not in the property sets of IfcColumn in the IFC schema.

5.4. Document management

The systematic perspective to include all the activities that the historic building requires is solved by the BIM methodology when referring to documentary management. Each heritage intervention is developed in relation to the knowledge of the building structure to achieve all the research work [83] based on two processes: the analysis of the building, and major activities. The great deal of information in documentary

sources, such as reports, texts, and graphic documents, is generated to understand the building and archaeological nature of the CH. In this regard, the most appropriate structure is an ontological model for observation to preserve the conducted interventions. The 3D model of the column was built through semantic partitions with families. The ontology of the model followed the conceptual system of the information related to the geometric model segmentation. It represents the semantic breakdown framework in which the column is structured as per the point cloud segmentation: its plinth as the settling element of the main structure; the decorative base in the column; the shaft; the capital with vegetable details; and perpend and transverse arches from the column capital to the vault support. OWL is the most common language to represent ontologies [103]. It greatly facilitates the interpretation of web contents. Hence, the semantic information should be studied through OWL ontologies that welcome .xml and .rdf files.

The reliability degree of the geometric information is defined by the international specifications, known as LoD [104]. Using a classification system allows the model to be structured with known bases to define the attributes of each element, and this is very useful for companies or institutions working with new buildings. Normalisation and distribution are not studied in relation to movable and immovable CH assets. This study structured an HBIM project in which the semantic data were managed and included in the BIM digital platform, and the architectural elements were organised according to the GuBIMClass classification [92]. This classification derives from category 20, structural system, and its subcategories, 20.20 structure and 20.20.10 column, to later obtain a new subset of the column system in parts of 20.20.10.10 base- shaft-

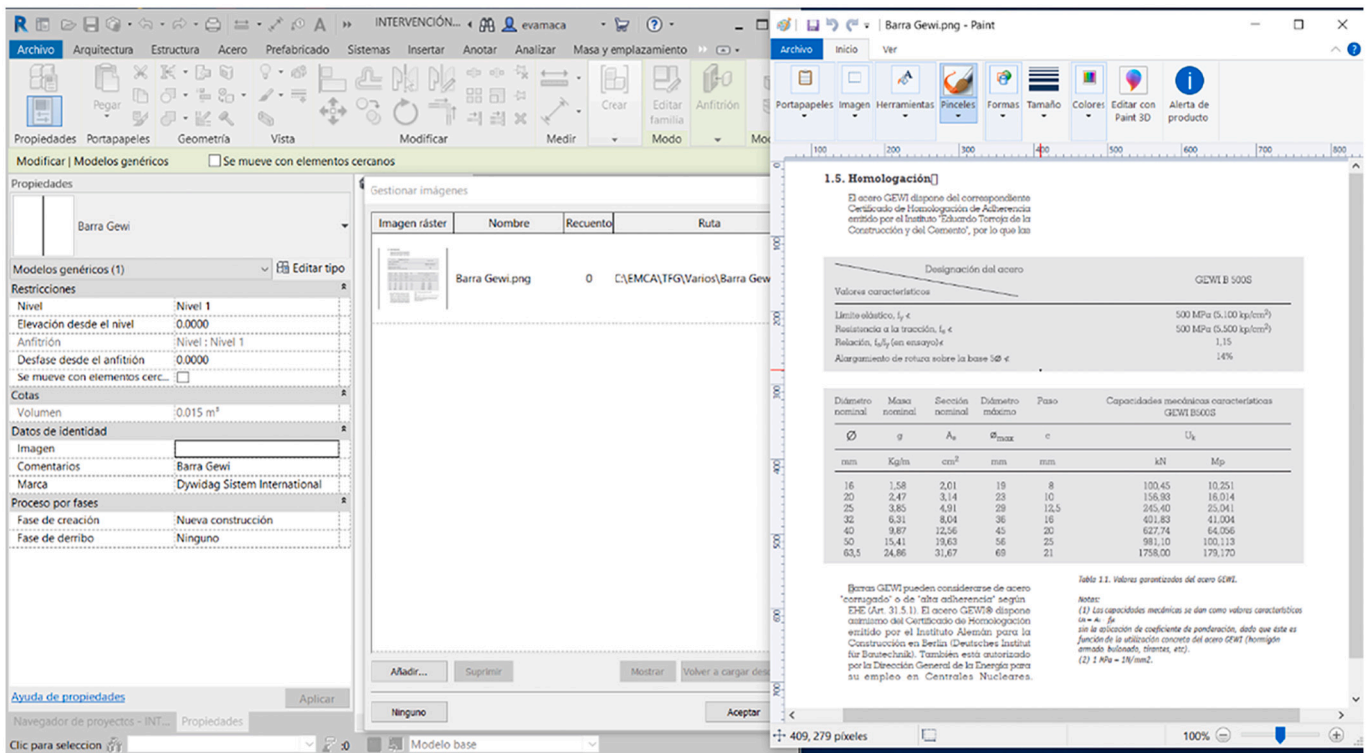


Fig. 17. Treatment data of the column included in the model of the Gawi bar family.

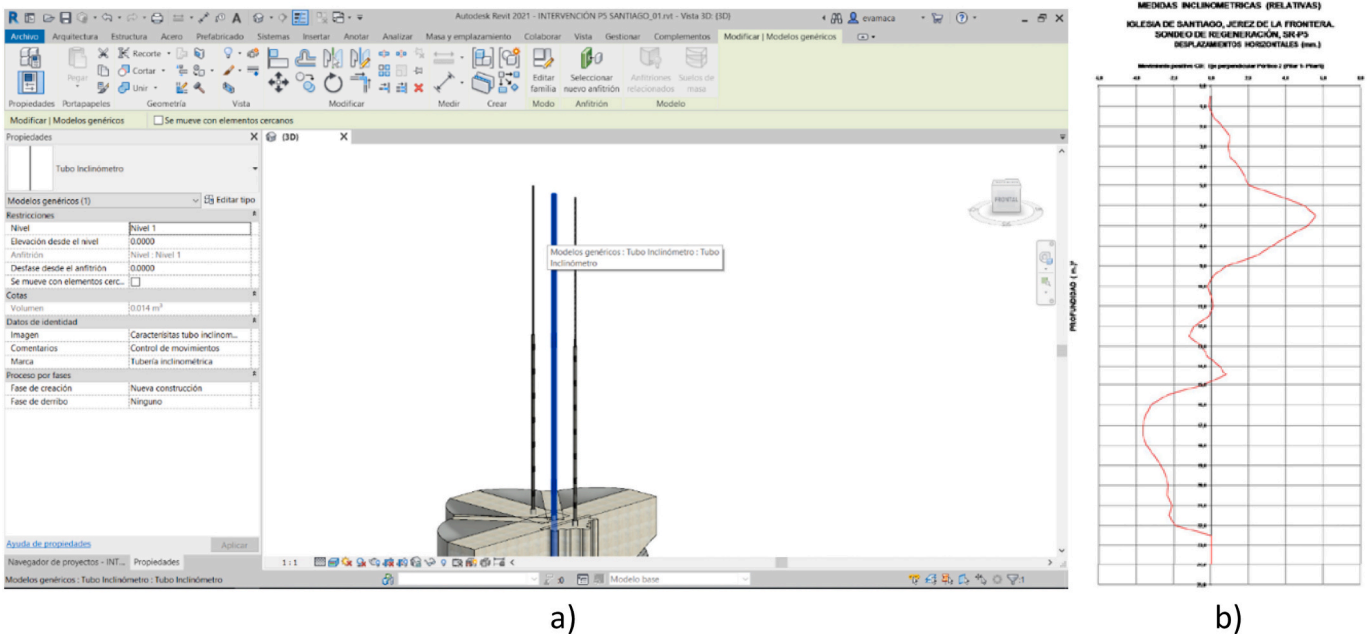


Fig. 18. a) Report in the inclinometer pipe family. b) Graphic report.

capital, and arches. Fig. 21 describes this development.

6. Discussion of the results

Managing CH is a difficult task that requires accurate tools to achieve geometrically suitable results. Two concepts could be useful to change the reality when applying the BIM methodology to heritage. One of them is the systematic approach, the logic sequence of the execution processes of a HBIM project. In the examined case study, an experimental

campaign was conducted to obtain MDCs through TLS or SfM [60]. The point cloud was registered to create a global georeferenced point cloud. This could be carried out using software packages such as 3DReshaper or Leica Cyclone Register 360, which provided tools to remove the noise before exporting the point cloud [27]. After obtaining the parametric objects through adaptive meshes, the results were processed to proceed to the evaluation of the model so that the geometric deformations and variations could be analysed. Research studies in the CH domain are increasingly focusing on structural analysis in a BIM environment [105].

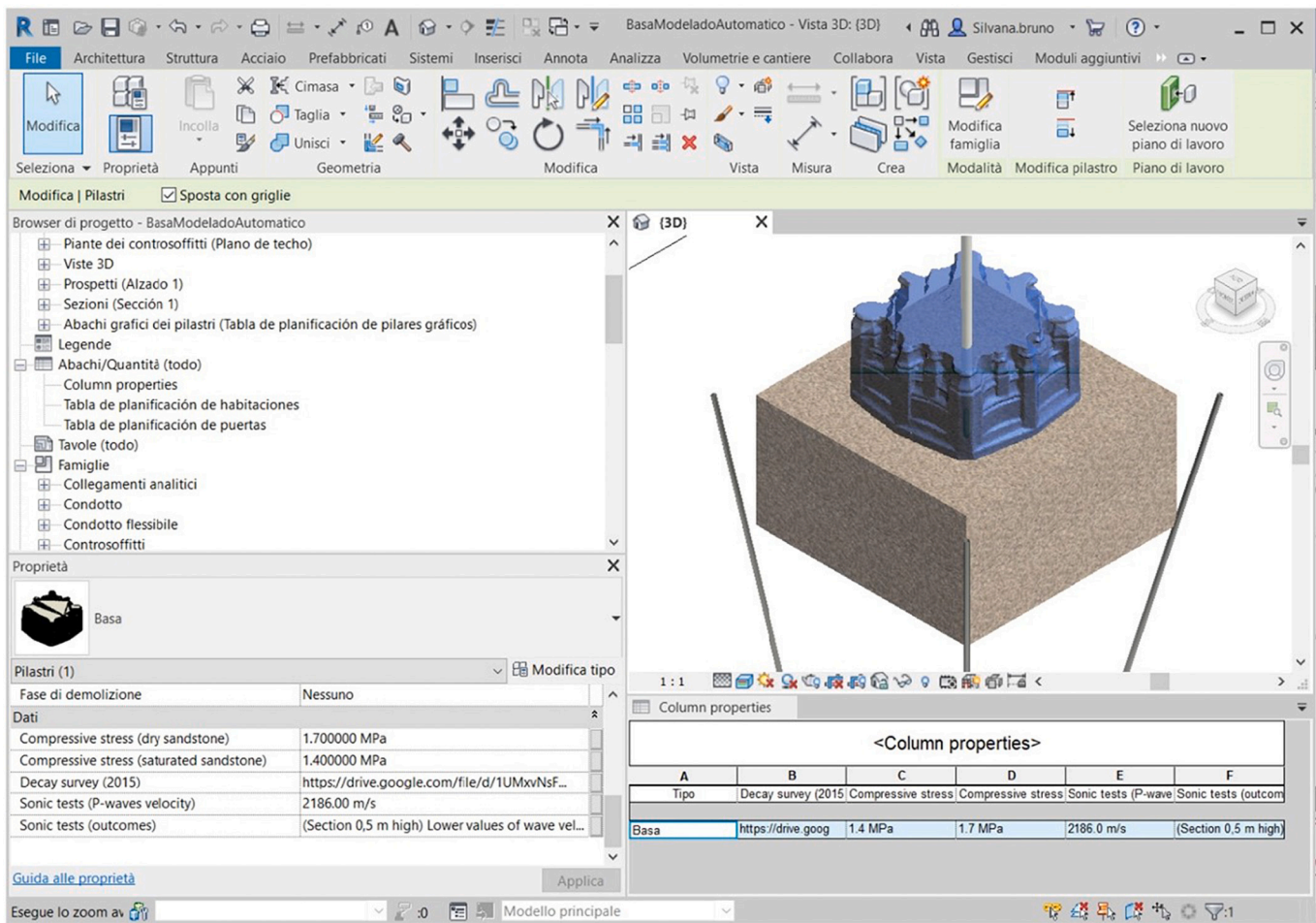


Fig. 19. BIM environment to manage data from diagnostic tests of the base column.

Recent research works have achieved the analysis of the structural deformations of historic buildings by using the codification of an algorithm within the applicability of the BIM platform. Although it could be initially applied to historic buildings, it could also be used for new buildings. Without using complex structural software and alternative flows, an algorithm from the digital platform to analyse the deviations between MDCSs and the (ideal) parametric objects enables the real-time assessment of: i) the quality of the model built, and ii) the structural deformations that could take place throughout the life cycle of the building. This new paradigm would imply that researchers, lecturers, and experts in CH change the concept of usability of BIM platforms, considering a comprehensive HBIM project in relation to its historical, evolutionary, structural, and information management analysis, which is multidisciplinary for the effective conservation of the CH asset.

Further investigation involves setting categories and the corresponding attributes in the BIM project, and the inclusion of semantic information of the construction model. The other concept is the systemic approach whose main point is its own system concept, a set of interrelated elements with the common goal of building a graphic and numeric information model with three-dimensional characteristics to integrate the dynamic evolution of the heritage assets into a dynamic model [106]. Therefore, this original contribution proposes both a systematic and a systemic approach. First, the interventions conducted in the column were qualitatively described according to the evolution of building sequences. The workflow depicted in Fig. 3 shows the main aspects between the restoration project stages, the modelling environment, and the integration of the database. The next section was the segmentation of the structural units into parts so that the model was easily assessed and

built. This manual segmentation process was configured by morphological units, creating five levels that constituted significant changes in the column geometry. The manual segmentation has been sometimes used by researchers such as Boulaassal et al. [107], which allows for assessing the resulting parts. Another aspect to be highlighted is the assessment of the DT. The concept of DTs has several meanings. Al-Sehrawy and Kumar [108] determined 18 definitions for the term DT according to three aspects: identity and nature, goal and purpose, and the main constituents, elements, and components. As a result, the DT is considered as the construction of digital information of the asset in a physical system. The automation process in the BIM system was conducted through the combination of Dynamo and Revit. In this process, a mesh generated through Rhino software was converted into a Revit family. To understand the workflows that current BIM platforms such as ArchiCAD and Revit use to achieve DT parametric models through AM, the study sequence of the column base of the church was followed. Thus, this recently studied mesh-to-BIM working methodology constitutes a gap in the software's applicability. The logical sequence exposed in the workflow for ArchiCAD software in this research allows for achieving a DT being used by the BIM operators themselves. In the sequence through Revit, knowledge from mesh to BIM to a parametric DT should be available for experts in Dynamo and Revit. The use time in both cases is similar provided that the necessary know-how for its execution is available. One of the problems of the mesh-to-BIM process automation in Revit is that the mesh should be simplified by 50% of triangles used in the AM for ArchiCAD. The results obtained were an ideal model and a DT model generated from TLS_{iy} to a parametric object of column 5 of the Santiago Church in Jerez de la Frontera. The results from the deviation

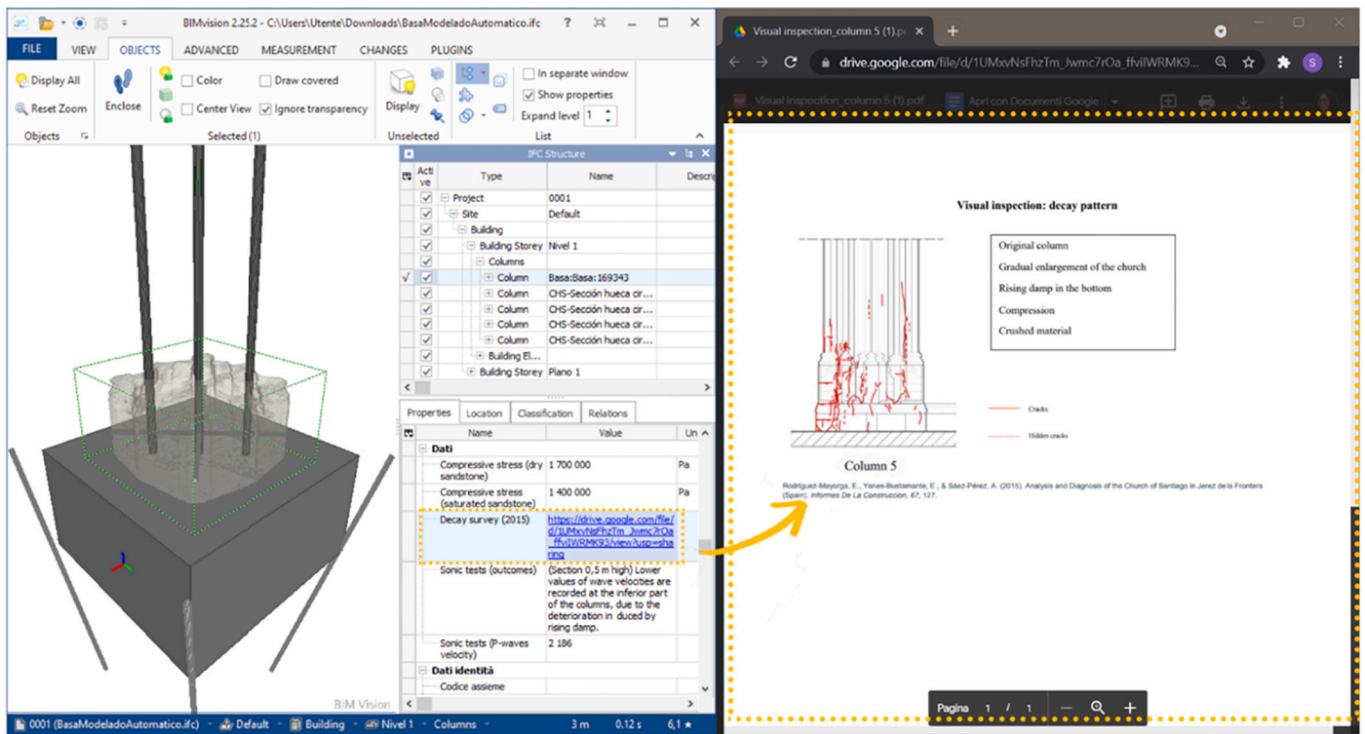


Fig. 20. Visualisation of customised IFC properties in the openIFC viewer BIMVision 2.25.2.

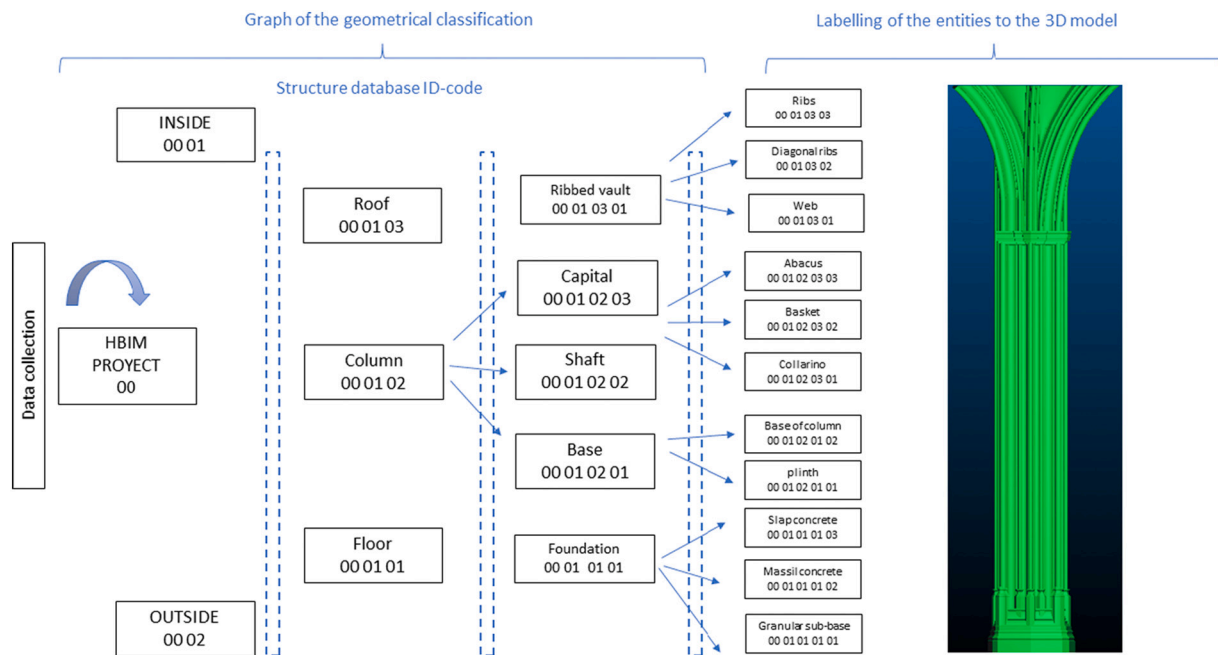


Fig. 21. Identification of categories.

evaluation between the global ideal model and the point cloud was approximately 6 cm.

Further, the column base automatically modelled from the mesh in a Revit family was studied. This base worked as a parametric object to add customised properties. In this case study, the properties required in the restoration process referred to the historical analysis, the results and reports of the diagnosis tests, the characterisation of the material of the mechanical properties, and the characteristics of the materials and technologies used for the consolidation. On the other hand, the BIM of

the base of the column was exported to IFCx4 Reference View, including IFC and customised parameters to be widely studied using .ifc viewers such as BIMVision (Fig. 20), Open IFC Visor, and Solibri Anywhere.

The use of images as properties in Revit does not allow to consult them in the IFC viewer because the images in .jpeg, and .tiff formats, among others, are not IFC type of data. This implies to provide reports and images in the working group as URL of shared files (a common or on-line server such as Google Drive or WeTransfer). In addition, the introduction of the parameter 'Sonic tests (P-waves velocity)' with data

type 'speed [m/s]' within the IfcColumn (building element) causes the loss of the reference measure unit in the IFC viewer because 'speed' is not in the property sets of IfcColumn in the IFC schema.

One of the goals of HBIM research is providing the heritage sector with a standardised terminology and semantics. There is a need of using classification systems in a HBIM context. The goal of ISO 12006-2 is that national systems allow the definitions of the standard to be compared. Using a classification system enables the organisation of the model by known bases to be shared among agents. Keynotes provides tools to classify and describe the elements of the restoration project. In this classification, the novelty is the component of treatments that are part of the construction model (Fig. 21). Nevertheless, Keynotes is a specialised proprietary add-on. The classification activity of the proposed approach also investigated the classification with Omniclass, Uniformat II, and Uniclass 2015, and demonstrated that they are not adapted for the historic building. The recommendation is to create further chapters and subchapters of them when a generic classification is not sufficient. However, Uniclass permits the upgrading of classes in the Revit platform (avoided for Omniclass); the criticality is represented by the absence of an international standardised encoding of these added items. Future remarks regard the need to work on a common and appropriate classification of construction systems in CH domain. Another was carried out on IFC export and navigation of the HBIM project. Again, these tasks required a custom mapping of construction classes, not internationally recognised.

7. Conclusions

In architectural restorations, the information to manage a heritage asset is obtained by analysis teams that study the geometry of architectural sites, including churches, monasteries, and cathedrals. The building characterisation and its evolution over time is called building life cycle. From this point of view, this work presents the systematic process in which the interventions conducted according to an evolution of building sequences are qualitatively described. The first step involves new data acquisition technologies, which ease the capture of the conservation status and the geometric recording of the elements. The assessment process implies other stages included in this work as a new perspective until constructing the 3D digital model. Current BIM programmes allow for creating ideal 3D objects. Moreover, from the applicability of the new technologies, BIM platforms also welcome properties and characteristics from those technologies. Consequently, a replica is used to build the model. The operational effectiveness is greater when research studies and academic works are conducted, highlighting the new paradigm of BIM in heritage buildings. From this perspective, this work shows a full view of the possibilities of BIM platforms defined as a systematic approach. This paper focuses on the case study of the base of column no. 5 of the Santiago Church in Jerez de la Frontera. Here, based on automatic meshing from TLS data, the research also analyses the modelling workflow in a Revit family and in an adaptive mesh process in ArchiCAD. Regarding Revit, one of the problems of the automation through Dynamo of the Mesh-to-BIM process is that the mesh needs to be simplified so that the algorithm can process it. Further studies could assess the impact of this simplification on the geometric analysis of the model. Further insights derive from this study on the informative character of the ideal 3D model to support decision making for future interventions and maintenance activities at CH. For this reason, one objective was the data structure following and extending a standard data structure of the column components. This has been carried out as a preparatory activity to the future development of an ontological breakdown of the architectural building components to be enriched with semantics about construction evolution, previous interventions, decay mapping over time, and diagnostic tests. The interoperability of BIM is another aspect that has been pursued in this study. Thanks to the sharing of the BIM in the open IFC standard, which also contains customised attributes, consolidated and incremental

knowledge about the fabric will be available in the future. The choice of the presented case study is justified by the stratification of knowledge around a real artefact which was surveyed by geometric data acquisition techniques and reconstructed in a BIM project. Thus, this systematic approach could be scalable to use the methodology on other historic buildings and infrastructures, adapting the data structuring of the granular breakdown of the artefact under study.

Declaration of Competing Interest

None.

Data availability

No data was used for the research described in the article.

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References

- [1] M. Vecco, A definition of cultural heritage: from the tangible to the intangible, *J. Cult. Herit.* 11 (2010) 321–324, <https://doi.org/10.1016/j.culher.2010.01.006>.
- [2] S. Cursi, D. Simeone, I. Toldo, A semantic web approach for built heritage representation, in: G. Celani, D.M. Sperling, J.M.S. Franco (Eds.), 16th International Conference, CAAD Futures 2015, July 8–10, 2015, São Paulo, Brazil, 2015, pp. 383–401, <https://doi.org/10.1007/978-3-662-47386-3>.
- [3] S. Garagnani, A. Gaucci, E. Govi, *Archaeobim: Dallo scavo al building information modeling di una struttura sepolta. Il caso del tempio tuscanico di uni a marzabotto*, *Archeol. Calcolatori.* 27 (2016) 251–270.
- [4] S. Garagnani, A. Gaucci, P. Moscati, *Archaeo BIM, Theory, Processes and Digital Methodologies for the Lost Heritage*, Bologna, Bologna University Press, 2021, in: https://books.google.es/books?hl=es&lr=&id=Y_EFEAAAQBAJ&oi=fnd&pg=PA11&dq=+Garagnani+ArchaeoBIM.+Theory,+Processes+and+Digital+Methodologies+for+the+Lost+Heritage&ots=ObObp72bCA&ig=y2qKUyGfKbAAX8IkhDQNi5fSXM#v=onepage&q=GaragnaniArchaeoBIM.Theory%2CP (accessed June 13, 2022).
- [5] R. Mammoli, C. Mariotti, R. Quattrini, *Modeling the fourth dimension of architectural heritage: enabling processes for a sustainable conservation*, *Sustainability* 13 (2021) 5173.
- [6] M. Murphy, A. Chenux, An evaluation case study - A Historic Building Information Model (HBIM) of the leaning tower of Pisa, *Building* (2009) 1369–1377. <http://library.iated.org/view/MURPHY2009ANE> (accessed April 21, 2016).
- [7] C. Dore, M. Murphy, Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites, in: Proceedings of the 2012 18th International Conference on Virtual Systems and Multimedia, VSMM 2012: Virtual Systems in the Information Society, 2012, pp. 369–376, <https://doi.org/10.1109/VSMM.2012.6365947>.
- [8] S. Garagnani, *Building Information Modeling and real world knowledge: a methodological approach to accurate semantic documentation for the built environment*, in: 2013 Digital Heritage International Congress (DigitalHeritage), 2013, pp. 489–496.
- [9] S. Fai, K. Graham, Building information modelling and heritage documentation, in: XXIII CIPA International Symposium, Prague, Czech Republic, 12th–16th September, 2011, pp. 1–10. <https://pdfs.semanticscholar.org/b76a/6be1ab4c5c148757eac8c73dc7a5c2995999.pdf>.
- [10] R. Volk, J. Stengel, F. Schultmann, Automation in construction Building Information Modeling (BIM) for existing buildings — literature review and future needs, *Autom. Constr.* 38 (2014) 109–127, <https://doi.org/10.1016/j.autcon.2013.10.023>.
- [11] N. Hichri, C. Stefani, L. De Luca, P. Veron, G. Hamon, From point cloud to BIM: a survey of existing approaches, in: ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XL, 2013, pp. 343–348, <https://doi.org/10.5194/isprsarchives-XL-5-W2-343-2013>.
- [12] S. Logothetis, A. Delinasiou, E. Stylianidis, Building information modelling for cultural heritage: a review, in: ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences. II-5/W3, 2015, pp. 177–183, <https://doi.org/10.5194/isprsannals-II-5-W3-177-2015>.
- [13] D.P. Pocobelli, J. Boehm, P. Bryan, J. Still, J. Grau-Bové, BIM for heritage science: a review, *Herit. Sci.* 6 (2018) 23–26, <https://doi.org/10.1186/s40494-018-0191-4>.

- [14] F. López, P. Leronés, J. Llamas, J. Gómez-García-Bermejo, E. Zalama, A review of Heritage Building Information Modeling (H-BIM), in: *Multimodal Technologies and Interaction* vol. 2, 2018, p. 21.
- [15] M. Radanovic, K. Khoshelham, C. Fraser, Geometric accuracy and semantic richness in heritage BIM: a review, in: *Digital Applications in Archaeology and Cultural Heritage* vol. 19, 2020, pp. 1–12, <https://doi.org/10.1016/j.daach.2020.e00166>.
- [16] S. Bruno, M. De Fino, F. Fatiguso, Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management, *Autom. Constr.* 86 (2018) 256–276, <https://doi.org/10.1016/j.autcon.2017.11.009>.
- [17] A. Khalil, S. Stravrovadis, H-BIM and the domains of data investigations of heritage buildings current state of the art, in: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Copernicus GmbH, 2019, pp. 661–667, <https://doi.org/10.5194/isprs-Archives-XLII-2-W11-661-2019>.
- [18] A. Osello, The future of drawing with BIM for engineers and architects, in: *Dario Flaccovio Editore Srl*, 2012, pp. 1–323. https://scholar.google.es/scholar?hl=es&as_sdt=0%2C5&q=The+future+of+drawing+with+BIM+for+Engineers+and+Architects&btnG= (accessed March 10, 2021).
- [19] N. Bruno, From Survey to Analysis for Cultural Heritage Management: A New Proposal for Database Design in BIM, Ph.D. thesis, Università di Parma, 2017. Dipartimento di Ingegneria e Architettura, https://www.academia.edu/download/60400385/Bruno_Nazarena_Autec20190826-64045-1hgox36.pdf (accessed March 10, 2021).
- [20] X.J. Cheng, W. Jin, Study on reverse engineering of historical architecture based on 3D laser scanner, *J. Phys. Conf. Ser.* (2006) 843, <https://doi.org/10.1088/1742-6596/48/1/160>. IOP Publishing.
- [21] A. Santoni, R. Martín-Talaverano, R. Quattrini, J.I. Muirillo-Fragero, HBIM approach to implement the historical and constructive knowledge. The case of the Real Colegiata de San Isidoro (León, Spain), *Virtual Archaeol. Rev.* 12 (2021) 49–65, <https://doi.org/10.4995/VAR.2021.13661>.
- [22] J. Moyano, J. León, J.E. Nieto-Julían, S. Bruno, Semantic interpretation of architectural and archaeological geometries: point cloud segmentation for HBIM parameterisation, *Autom. Constr.* 130 (2021) 1–16, 103856, <https://doi.org/10.1016/J.AUTCON.2021.103856>.
- [23] M. Capone, E. Lanzara, Scan-to-BIM vs 3D ideal model HBIM: parametric tools to study domes geometry, in: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* vol. 42, 2019, pp. 219–226.
- [24] M. Bonduel, M. Bassier, M. Vergauwen, P. Pauwels, R. Klein, Scan-to-bim output validation: towards a standardized geometric quality assessment of building information models based on point clouds, in: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 42, 2017, pp. 45–52, <https://doi.org/10.5194/isprs-archives-XLII-2-W8-45-2017>.
- [25] F. Banfi, The integration of a scan-to-hbim process in bim application: the development of an add-in to guide users in autodesk revit, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII-2/W11* (2019) 141–148, <https://doi.org/10.5194/isprs-Archives-XLII-2-W11-141-2019>.
- [26] M. Andriasyan, J. Moyano, J.E. Nieto-Julían, D. Antón, From point cloud data to building information modelling: an automatic parametric workflow for heritage, *Remote Sens.* 12 (2020) 1094.
- [27] D. Costantino, M. Pepe, A.G. Restuccia, Scan-to-HBIM for conservation and preservation of Cultural Heritage building: the case study of San Nicola in Montedoro church (Italy), *Appl. Geomat.* (2021) 1–15, <https://doi.org/10.1007/s12518-021-00359-2>.
- [28] H. Macher, T. Landes, P. Grussenmeyer, From point clouds to building information models: 3D semi-automatic reconstruction of indoors of existing buildings, *Appl. Sci. (Switzerland)* 7 (2017) 1–30, <https://doi.org/10.3390/app7101030>.
- [29] S. Hong, J. Jung, S. Kim, H. Cho, J. Lee, J. Heo, Semi-automated approach to indoor mapping for 3D as-built building information modeling, *Comput. Environ. Urban. Syst.* 51 (2015) 34–46, <https://doi.org/10.1016/J.COMPENVURBSYS.2015.01.005>.
- [30] C. Thomson, J. Boehm, Automatic geometry generation from point clouds for BIM, *Remote Sens.* 7 (2015) 11753–11775, <https://doi.org/10.3390/rs70911753>.
- [31] F. Remondino, S. El-Hakim, Image-based 3D modelling: a review, *Photogramm. Rec.* 21 (2006) 269–291, <https://doi.org/10.1111/j.1477-9730.2006.00383.x>.
- [32] D. Antón, B. Medjdoub, R. Shrahily, J. Moyano, Accuracy evaluation of the semi-automatic 3D modeling for historical building information models, *Int. J. Arch. Herit.* 12 (2018) 790–805, <https://doi.org/10.1080/15583058.2017.1415391>.
- [33] M. Canciani, C. Falcolini, M. Saccone, G. Spadafora, From point clouds to architecture models: algorithms for shape reconstruction, in: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* vol. XL-5/W1, 2013, pp. 27–34, <https://doi.org/10.5194/isprsarchives-xl-5-w1-27-2013>.
- [34] C. Tommasi, C. Achille, F. Fassi, From point cloud to BIM: a modelling challenge in the Cultural Heritage field, *Isprs - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLI-B5* (2016) 429–436, <https://doi.org/10.5194/isprsarchives-XLI-B5-429-2016>.
- [35] D. Miller, Nathan, Stasiuk, A novel mesh-based workflow for complex geometry in BIM, in: *Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 2017, pp. 404–413.
- [36] J. Zhu, P. Wu, M. Chen, M.J. Kim, X. Wang, T. Fang, Automatically processing IFC clipping representation for BIM and GIS integration at the process level, *Appl. Sci.* 10 (2020) 2009, <https://doi.org/10.3390/app10062009>.
- [37] D. Oreni, R. Brumana, S. Della Torre, F. Banfi, L. Barazzetti, M. Previtali, Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila), *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. II-5* (2014) 267–273, <https://doi.org/10.5194/isprsannals-II-5-267-2014>.
- [38] W. Solihin, C. Eastman, Y.C. Lee, Multiple representation approach to achieve high-performance spatial queries of 3D BIM data using a relational database, *Autom. Constr.* 81 (2017) 369–388, <https://doi.org/10.1016/j.autcon.2017.03.014>.
- [39] L. Barazzetti, Parametric as-built model generation of complex shapes from point clouds, *Adv. Eng. Inform.* 30 (2016) 298–311, <https://doi.org/10.1016/j.aei.2016.03.005>.
- [40] X. Yang, P. Grussenmeyer, M. Koehl, H. Macher, A. Murtiyoso, T. Landes, Review of built heritage modelling: Integration of HBIM and other information techniques, *J. Cult. Herit.* 46 (2020) 350–360, <https://doi.org/10.1016/j.culher.2020.05.008>.
- [41] E. Rodríguez-Mayorga, E. Yanes-Bustamante, A. Sáez-Pérez, Analysis and diagnosis of the church of Santiago in Jerez de la Frontera (Spain), *Inform. Constr.* 67 (2015), <https://doi.org/10.3989/ic.15.030>.
- [42] F. Arcoja Vicenti, Arquitectura civil jerezana del siglo XVIII, in: *Revisión y nuevos datos 18*, Laboratorio de Arte, 2005, pp. 327–347, <https://doi.org/10.12795/LA.2005.i18.28>.
- [43] J.J. Moyano, J.A. Barrera, J.E. Nieto, D. Marín, D. Antón, A geometrical similarity pattern as an experimental model for shapes in architectural heritage: a case study of the base of the pillars in the Cathedral of Seville and the church of Santiago in Jerez, Spain, in: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* vol. XLII-2/W3, 2017, pp. 511–517, <https://doi.org/10.5194/isprs-archives-XLII-2-W3-511-2017>.
- [44] Alonso Ruiz and Jiménez Martin, La traça de la iglesia de Sevilla. <https://scholar.google.com/scholar?cluster=9368929990358536425&hl=en&oi=scholar>, 2009 (accessed March 5, 2021).
- [45] E. Rodríguez Mayorga, A. Cobo, E. Yanes, A. Saez, The repair of the structure of Santiago's Church (Jerez De La Frontera, Spain) using grout-injection, *Int. J. Arch. Herit.* 13 (2019) 1234–1251, <https://doi.org/10.1080/15583058.2018.1515273>.
- [46] E. Rodríguez-Mayorga, Rehabilitación del Templo Parroquial de Santiago Apóstol en Jerez de la Frontera: anamnesis, diagnosis, terapia y control, in: *Universidad de Sevilla*, 2011.
- [47] CTN 81/SC 2, Means of Collective Protection at Work, UNE-EN 1263-1:2004 - Safety Nets - Part 1: Safety Requirements, Test Methods, 2004.
- [48] J. Santamar, L. Rioja, La intersección inversa: Método geométrico, Topográfico y Cartográfico, in: *Internacional Graphic Engineering, X I V Congreso*, 2002.
- [49] J. Moyano, J.E. Nieto-Julían, D. Antón, E. Cabrera, D. Bienvenido-Huertás, N. Sánchez, Suitability study of structure-from-motion for the digitisation of architectural (heritage) spaces to apply divergent photograph collection, *Symmetry.* 12 (2020) 1981, <https://doi.org/10.3390/sym12121981>.
- [50] P. Mañana-Borrazás, A. Rodríguez-Paz, R. Blanco-Rotea, An experience in the application of the 3D Laser Scanner to the documentation and analysis processes of Built Heritage: its application to Santa Eulalia de Bóveda (Lugo) and San Fiz de Solovio (Santiago de Compostela), in: *Arqueología de La Arquitectura*, 2008, pp. 15–32, <https://doi.org/10.3989/arqarqt.2008.i5>.
- [51] M.J. González Muñoz, A.J. Rueda Ruiz, R.J. Segura Sánchez, C.J. Ogáyar Anguita, A. Esteban Hoyas, J. Lara, Uso de sistemas basados en escáner 3D para digitalización y estudio del patrimonio arqueológico, *Virtual Archaeol. Rev.* 1 (2010) 99, <https://doi.org/10.4995/var.2010.5128>.
- [52] D. Antón García, J.J. Moyano Campos, A. Souto Galván, J.E. Nieto Julián, 3D scanning and data management for the conservation status analysis of Nottingham general cemetery, United Kingdom, in: *XIV International Conference on Graphic Expression Applied to Building*, 2019.
- [53] S. Kim, S. Kim, D.-E. Lee, 3D Point cloud and BIM-based reconstruction for evaluation of project by as-planned and as-built, *Remote Sens.* 12 (2020) 1457, <https://doi.org/10.3390/rs12091457>.
- [54] T. Landes, G. Kuhnle, R. Bruna, 3D modeling of the strasbourg's cathedral basements for interdisciplinary research and virtual visits, in: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing*, 2015, pp. 263–270, <https://doi.org/10.5194/isprsarchives-XL-5-W7-263-2015>.
- [55] K. Pukanská, The Application of Terrestrial Laser Scanning for Spatial Visualization of Laboratories of the BERG Faculty. <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.310.5190&rep=rep1&type=pdf>, 2012 (accessed March 25, 2021).
- [56] Geosystems, Leica Geosystems, Leica FlexLine TS02/TS06/TS09 User Manual, Leica Geosystems AG, Heinrich-Weid-Strasse, CH-9435 Heerbrugg, Switzerland, 2008. <https://leica-geosystems.com/> (accessed March 16, 2020).
- [57] L. De Luca, C. Busayarat, C. Stefani, P. Véron, M. Florenzano, A semantic-based platform for the digital analysis of architectural heritage, *Comput. Graph. (Pergamon)* 35 (2011) 227–241, <https://doi.org/10.1016/j.cag.2010.11.009>.
- [58] N. Bruno, R. Roncella, HBIM for conservation: a new proposal for information modeling, *Remote Sens.* 11 (2019) 1751, <https://doi.org/10.3390/rs11151751>.
- [59] V. Bagnolo, R. Argiolas, A. Cuccu, HBIM for archaeological sites: from SFM based survey to algorithmic modeling, in: *International Archives of the*

- Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives vol. XLII-2, 2019, pp. 57–63, <https://doi.org/10.5194/isprs-archives-XLII-2-W9-57-2019>.
- [60] J. Moyano, J.E. Nieto-Julián, D. Bienvenido-Huertas, D. Marín-García, Validation of close-range photogrammetry for architectural and archaeological heritage: analysis of point density and 3d mesh geometry, *Remote Sens.* 12 (2020) 3571, <https://doi.org/10.3390/rs12213571>.
- [61] F. Chiabrando, M. Lo Turco, C. Santagati, Digital invasions: from point clouds to historical building object modeling (h-BOM) of a unesco WHL site, in: *International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences - ISPRS Archives* 42, 2017, pp. 171–178, <https://doi.org/10.5194/isprs-archives-XLII-2-W3-171-2017>.
- [62] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques, *Autom. Constr.* 19 (2010) 829–843, <https://doi.org/10.1016/j.autcon.2010.06.007>.
- [63] J.A.H. Tortosa, D.T. Fuentes, M.L. Cereceda, Y.S. Berrio, The façade of the church of nuestra señora de la asunción in biar (Spain): From point cloud to HBIM, *WIT Trans. Built Environ.* 169 (2017) 69–77, <https://doi.org/10.2495/BIM170071>.
- [64] C. Bolognesi, F. Fiorillo, D. Aiello, Three renaissance vaults in Milan. cultural heritage and digital workflows for BIM modelling, in: *Advances in Intelligent Systems and Computing*, Springer Verlag, 2020, pp. 202–211, https://doi.org/10.1007/978-3-030-20216-3_19.
- [65] M. Intignano, S.A. Biancardo, C. Oretto, N. Viscione, R. Veropalumbo, F. Russo, G. Ausiello, G. Dell'acqua, A scan-to-BIM methodology applied to stone pavements in archaeological sites, *Heritage* 4 (2021) 3032–3049, <https://doi.org/10.3390/HERITAGE404169>.
- [66] G. ArchiCAD, PARAM-O – Graphisoft. <https://graphisoft.com/es/downloads/param-o>, 2021 (accessed September 2, 2021).
- [67] G. ArchiCAD, Python – Graphisoft. <https://graphisoft.com/downloads/python>, 2021 (accessed September 2, 2021).
- [68] F.J. López, P.M. Leronés, J. Llamas, J. Gómez-García-Bermejo, E. Zalama, A framework for using point cloud data of heritage buildings toward geometry modeling in a BIM context: a case study on Santa Maria La Real De Mave Church, *Int. J. Arch. Herit.* 11 (2017) 965–986, <https://doi.org/10.1080/15583058.2017.1325541>.
- [69] D. Girardeau-Montaut, *CloudCompare Point Cloud Processing Workshop*, 2019, pp. 1–38. www.cloudcompare.org@CloudCompareGPL (accessed January 28, 2021).
- [70] J. Moyano, C.P. Odriozola, J.E. Nieto-Julián, J.M. Vargas, J.A. Barrera, J. León, Bringing BIM to archaeological heritage: interdisciplinary method/strategy and accuracy applied to a megalithic monument of the Copper Age, *J. Cult. Herit.* (2020), <https://doi.org/10.1016/j.culher.2020.03.010>.
- [71] X. Yang, Y.-C. Lu, A. Murtiyoso, M. Koehl, P. Grussenmeyer, HBIM modeling from the surface mesh and its extended capability of knowledge representation, *Isprs Int. J. Geo-Inf.* 8 (2019) 301, <https://doi.org/10.3390/ijgi8070301>.
- [72] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques, *Autom. Constr.* 19 (2010) 829–843, <https://doi.org/10.1016/j.autcon.2010.06.007>.
- [73] J. Pierson, *Package Case Study - Mesh Toolkit | The Dynamo Primer*, *Dynamo*. https://primer.dynamobim.org/11_Packages/11-2_Mesh-Toolkit.html, 2019 (accessed June 7, 2021).
- [74] N. Miller, HOW TO: Convert a Mesh – Proving Ground Apps, Apps, PG, 2021. <https://apps.provingground.io/docs/conveyor-documentation/how-to-convert-a-mesh/#workflow-with-rhino-mesh-object> (accessed June 7, 2021).
- [75] Eric Boehlk, *Mesh Import from OBJ File - Revit App - BIM Consulting*, Truevis. Com, 2021. <https://truevis.com/revit-mesh-import/> (accessed June 7, 2021).
- [76] Y.D. Rajendra, S.C. Mehrotra, K.V. Kale, R.R. Manza, R.K. Dhumal, A.D. Nagne, D. Vibhute, S. Ramanujan, G. Chair, Evaluation of partially overlapping 3D point cloud's registration by using ICP variant and cloudcompare, *Isprs - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XL-8* (2014), <https://doi.org/10.5194/isprsarchives-XL-8-891-2014>.
- [77] J.E. Nieto-Julián, D. Antón, J.J. Moyano, Implementation and management of structural deformations into historic building information models, *Int. J. Arch. Herit.* 0 (2019) 1–14, <https://doi.org/10.1080/15583058.2019.1610523>.
- [78] M. Pepe, D. Costantino, V.S. Alfio, A.G. Restuccia, N.M. Papalino, Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site, *J. Cult. Herit.* 50 (2021) 115–125, <https://doi.org/10.1016/j.culher.2021.05.006>.
- [79] D. Lague, N. Brodu, J. Leroux, Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (N-Z), *ISPRS J. Photogramm. Remote Sens.* 82 (2013) 10–26, <https://doi.org/10.1016/j.isprsjprs.2013.04.009>.
- [80] T.S. Kalyan, P.A. Zadeh, S. Staub-French, T.M. Froese, Construction quality assessment using 3D as-built models generated with project Tango, *Proc. Eng.* (2016) 1416–1423, <https://doi.org/10.1016/j.proeng.2016.04.178>. Elsevier Ltd.
- [81] J.E. Nieto-Julián, L. Lara, J. Moyano, Implementation of a TeamWork-HBIM for the management and sustainability of architectural heritage, *Sustainability*. 13 (2021) 2161, <https://doi.org/10.3390/su13042161>.
- [82] A. Iglesias Castro, *Ontología BIM*. <https://comum.rcaap.pt/handle/10400.26/18739>, 2016 (accessed April 13, 2021).
- [83] M. Acierno, S. Cursi, D. Simeone, D. Fiorani, Architectural heritage knowledge modelling: an ontology-based framework for conservation process, *J. Cult. Herit.* 24 (2017) 124–133, <https://doi.org/10.1016/j.culher.2016.09.010>.
- [84] T. Messaoudi, P. Véron, G. Halin, L. De Luca, An ontological model for the reality-based 3D annotation of heritage building conservation state, *J. Cult. Herit.* (2017), <https://doi.org/10.1016/j.culher.2017.05.017>.
- [85] R.J. Scherer, P. Katranuschkov, BIMification: how to create and use BIM for retrofitting, *Adv. Eng. Inform.* 38 (2018) 54–66, <https://doi.org/10.1016/j.aei.2018.05.007>.
- [86] I.O. for S. (ISO), ISO 16739:2013—Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries. <https://www.iso.org/standard/51622.html>, 2013.
- [87] E. Häggström, Ekholm Lars, Building Classification for BIM-Reconsidering the Framework, CIB W78-W102 2011, <http://lup.lub.lu.se/record/2201252>, 2011 (accessed March 24, 2021).
- [88] G. ArchiCAD, BIM Content Packages – Graphisoft. https://graphisoft.com/downloads/archicad/bim_data, 2021 (accessed September 3, 2021).
- [89] T. Construction Specifications Institute, C. Specifications Canada, UniFormat TM A Uniform Classification of Construction Systems and Assemblies, 2021.
- [90] C. Isabel, E. Barbosa, Automatización de la asignación de códigos de sistemas de clasificación de elementos de un proyecto de construcción modelado en REVIT, 2019.
- [91] J. Park, H. Cai, WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation, *Autom. Constr.* 77 (2017) 15–23, <https://doi.org/10.1016/j.autcon.2017.01.021>.
- [92] EspacioBIM, GuBIMClass, ¿qué es GuBIMClass? | Espacio BIM. <https://www.espaciobim.com/gubimclass>, 2021 (accessed April 8, 2021).
- [93] O.C. System, OmniClass® - Construction Specifications Institute. <https://www.csiresources.com/standards/omniclass>, 2021 (accessed April 8, 2021).
- [94] P. Argenziano, A. Avella, S. Albanese, Building materials, ionizing radiation and HBIM: a case study from Pompei (Italy), *Buildings* 8 (2018) 18, <https://doi.org/10.3390/buildings8020018>.
- [95] C.K. Cogima, R.V.D.C. Nascimento, P.V.V. De Paiva, M.A.G. de Carvalho, E. Dezen-Kempter, Scan-to-HBIM aplicado a igreja da Pampulha de Oscar Niemeyer, *Gestão Tecnol. Projetos* 15 (2020) 117–134, <https://doi.org/10.11606/gtp.v15i1.152828>.
- [96] I. Brilakis, M. Lourakis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, A. Makhmalbaf, Toward automated generation of parametric BIMs based on hybrid video and laser scanning data, in: *Advanced Engineering Informatics*, Elsevier, 2010, pp. 456–465, <https://doi.org/10.1016/j.aei.2010.06.006>.
- [97] G. Bacci, F. Bertolini, M.G. Bevilacqua, G. Caroti, I. Martínez-Espejo Zaragoza, M. Martino, A. Piemonte, Hbim methodologies for the architectural restoration. The case of the ex-church of san quirico all'olivo in lucca, tuscan, in: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Copernicus GmbH, 2019, pp. 121–126, <https://doi.org/10.5194/isprs-archives-XLII-2-W11-121-2019>.
- [98] E.S. Malinverni, F. Mariano, F. Di Stefano, L. Petetta, F. Onori, Modelling in hbim to document materials decay by a thematic mapping to manage the cultural heritage: the case of “chiesa della pietà” in fermo, in: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Copernicus GmbH, 2019, pp. 777–784, <https://doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019>.
- [99] Biblus, IFC Class Mapping File. <https://biblus.accasoftware.com/en/ifc-class-mapping-file/>, 2020 (accessed June 23, 2022).
- [100] I.S. Platform, Code Assembly. <https://codeassembly.io/>, 2022 (accessed June 14, 2021).
- [101] S. Bruno, F. Fatiguso, Building conditions assessment of built heritage in historic building information modeling, *Int. J. Sustain. Dev. Plan.* 13 (2018) 36–48, <https://doi.org/10.2495/SDP-V13-N1-36-48>.
- [102] Modelical campus, Notas clave - Cómo se usan en Revit - Modelical. <https://www.modelical.com/es/gdocs/keynotes/>, 2022 (accessed June 16, 2021).
- [103] OWL, OWL Web Ontology Language Overview. <https://www.w3.org/TR/2004/REC-owl-features-20040210/>, 2004 (accessed June 13, 2022).
- [104] M. Bolpagni, BIM ThinkSpace: The Many Faces of 'LOD'. <https://www.bimthinkspace.com/2016/07/the-many-faces-of-lod.html>, 2016 (accessed April 8, 2021).
- [105] M. Valinejadshoubi, A. Bagchi, O. Moselhi, Development of a BIM-based data management system for structural health monitoring with application to modular buildings: case study, *J. Comput. Civ. Eng.* 33 (2019) 05019003, [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000826](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000826).
- [106] P. Rodríguez-González, A. Luis Muñoz-Nieto, S. del Pozo, L. Javier Sanchez-Aparicio, D. Gonzalez-Aguilera, L. Micoli, S. Gonizzi Barsanti, G. Guidi, J. Mills, K. Fieber, I. Haynes, B. Hejmanowska, 4D Reconstruction and Visualization of Cultural Heritage: Analyzing Our Legacy through Time, 2022, <https://doi.org/10.5194/isprs-archives-XLII-2-W3-609-2017>.
- [107] H. Boulaassal, T. Landes, P. Grussenmeyer, F. Tarsha-kurdi, Automatic segmentation of building facades using Terrestrial Laser Data, in: *ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007*, 2007, pp. 65–70.
- [108] R. Al-Sehrawy, B. Kumar, Digital twins in architecture, engineering, construction and operations, in: *A Brief Review and Analysis, Lecture Notes in Civil Engineering* 98, 2020, pp. 924–939, https://doi.org/10.1007/978-3-030-15295-8_64.