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Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage.

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Abstract

Maintaining the structure and ornaments of historical buildings is essential to preserve cultural heritage in any society. Thus, dating the state and the evolution of the elements requires a special treatment, including the application of both advanced numerical analysis and non-invasive data acquisition techniques. In the latter, making digital copies of geometries through 3D reconstruction models is of great interest to compare and analyse structural evolutionary data accurately. For this purpose, appropriate software with containers of information correlated to the parametric elements in a BIM environment should be used. However, it is imperative to advance from static to dynamic models to collect the structural transformations caused by both the pass of time and other factors. The methodology followed in this paper is based on the experimentation by creating digital twins. The portico of a courtyard in a historical building from the 18th century was used as test bed. Based on the bibliographical recommendations, the terrestrial laser scanner is applied as a technique to acquire accurate data. The point cloud is used as a referential auxiliary to survey the model in the BIM platform with the Revit software. To assess the quality of the model built and to analyse the structural deviations between the parametric model and the actual geometry, the Dynamo script is used. To validate the experimentation, structural deviations are measured using both the parametric model and the point cloud with CloudCompare, a software for data treatment. The results were very positive because the deviation between the data obtained by Dynamo® and CloudCompare in the most unfavourable construction unit was between 0.5 and 1.17 cm, so these techniques are highly appropriate to review visual records and to analyse structural deviations. This new approach presents a new gap in the 3D reconstruction to date and control architectural structures, particularly in historical buildings.

Keywords: HBIM, terrestrial laser scanning, generative algorithms, structural systems reverse engineering, cultural management

1.- Introduction

Preserving heritage is essential in the cultural life of today's society. For this reason, structures and ornaments should be appropriately maintained throughout historical buildings' life cycle. Modern buildings are today subjected to a strong regulatory quality control, unlike historical buildings. Thus, determining the structural conditions of these immovable assets requires a special treatment not just through an advanced numerical analysis [1], but through non-invasive techniques consolidated under the umbrella of the European Federation for Non-Destructive Testing (EFNDT). Assessment techniques include the Structure from Motion/ Multi-View-Stereo (SfM/MVS) and the Terrestrial Laser Scanner (TLS), which are data acquisition techniques that provide a copy of the geometric surface of the elements to be analysed. These

techniques are very interesting to be applied in heritage buildings as these buildings usually have singularities in comparison with the other buildings, such as the composition of their geometry. Comparing and analysing these geometries, which are generally complex, by using these techniques could be an effective and accurate tool to study structural units. The elements that could be identified are pathological symptoms, cracks, collapse in walls and columns, deflections of horizontal elements, and detachments of stone elements, among others. Therefore, the use of the reverse engineering through SfM and TLS could be a non-destructive technique of great interest to assess and analyse the deformations of structural elements. In the diagnosis phase in which the building's health is assessed, the geometry could be analysed as a pattern method. Jiang et al. [2] reviewed the use of the short-range photogrammetry in both the deformation of bridges and the measurement of their geometry. Xu et al. [1] used TLS for the static and dynamic analysis of the structural deformations of arches, concluding that placing sensors in structural elements is not required with this technique, unlike other procedures. The analysis is not just organoleptic through visual inspection tasks that could interpret structural damages; it is complemented with other analyses. Some methodological studies are focused on immersive environments between digital models and teledetection to diagnose the preservation of cultural heritage (CH) [3].

Today, architecture and construction (AC) in the 3D reconstruction model is fundamental to preserve CH. The geometry involved is usually complex, so the CAD/BIM software should be appropriately selected, and effective modelling tools should be used to be approached as accurate as possible, also considering time. BIM digital platforms represent a new paradigm both in the Architecture, Engineering and Construction (AEC) industry and the academic and scientific area. These 3D digital reconstructions are also containers of information correlated to the parametric elements. However, the construction model is a theoretical model built by the operator by using primitive geometries, i.e., drawings [4] or point clouds [5,6]. This model does not consider structural transformations due to the pass of time or those caused by natural circumstances (e.g., earthquakes and hurricanes), among other external agents. For this reason, there is a knowledge gap related to the assessment in various periods of the quality of the model built, so the structural deviations between the theoretical model and Massive Data Capture Systems (MDCSs) should be analysed. This process presents a new approach in architectural structures and determines processes to consolidate 3D records that could be inherited by future generations, developing technologies that ease complex analytic processes. The contribution of this paper is therefore focused on the codification of an algorithm within the applicability of the BIM digital platform, which analyses the structural deformations of buildings. It is initially applied to historical buildings, but it could also be applied to new buildings. Inferring an algorithm from the digital platform to analyse the deviations between MDCSs and (ideal) parametric objects means to assess in real time both the quality of the model built and the structural deformations that could take place throughout the life cycle of the building. This process simplifies the use of other complementary software within the structure scope, as well as alternative flows. This new research presents a new paradigm, thus making researchers, scholars, and professionals to change the use concept of BIM digital platforms.

2.- Literature review

Most studies focused on the preservation of CH recognise the importance of the Information and Communication Technologies (ICTs) to generate 3D geometric models of buildings, thus constituting an essential tool for building dissemination. In addition, these technologies could

solve key problems when rehabilitating a heritage building, such as controlling the deformations related to the static and dynamic structure behaviour. The study of these structures using 3D geometric models is of great interest. For this purpose, techniques to acquire accurate data should be used. Most topographic methods could be used as methods to control deformations, but their use is limited to isolated cases of deflection deviation or deviation intakes. Nevertheless, the reverse engineering fully monitors the surface according to the resolution quality of the point cloud. These technologies are increasingly effective and accurate thanks to the use of computational, mathematical and experimental procedures according to both the existing scientific literature [7,8] and the technological development. The 3D terrestrial laser scanning techniques are mainly new. These techniques produce a set of digital data points in the global point cloud (GPC), where each point is represented by coordinates in the 3D space [9]. The TLS laser scanner uses the reflection of a laser beam focused on objects to calculate precisely the geometry in a short time [10]. One of the advantages of this method is obtaining a point density of the order from 5 to 10 mm, thus obtaining accurate captures of the complex geometry in the CH during the 3D geometric reconstruction. A general review of the use of this technology in the architectural heritage could complete an extensive and broad study that is focused on the goals from another perspective. In this regard, some appealing studies have used the TLS given its high level of accuracy and applicability. Some interesting research works can be obtained from Mill et al. [11]. Tang and Akinci [12] developed workflows to obtain accurate point clouds in the geometries of bridges. In the line of creating parametric objects from a point set of the TLS [13] focused the study on the tube sector and their curvature. From the point of view of the surveying engineering, laser scanner techniques have recently increased the efficiency in the creation process of parametric elements and have developed a new perspective to create BIM information models. An example of the peak being developed by this research sector is the state of the art from scan to BIM presented by Antón et al. [14], who approached to the accuracy evaluation of the 3D modelling, and Mesrop et al. [15], who created an automatic parametric workflow applied to the CH.

Under this context, BIM applied to CH emerges, facing with two major challenges. On the one hand, the difficulty of having libraries containing historical architectural elements and details coinciding with architectural compositions, which are very different due to the long historical temporariness. On the other hand, the difficulty that these elements are true digital twins of the complex architectural sites.

The scientific literature published until now [16–19] has been focused on implementing the grammar of forms by the interactive edition of geometry, using software supported by the visual parametric programming. These systems provide the traditional design in architecture with many functionalities. For instance, computational languages, such as Python®, carries out essential repetitive tasks (listing tables and classifying typological areas, among others) and optimises the production of the model as regards times and error reductions. The usual commands of CAD/BIM applications are reinforced by using the Application Programming Interface (API) such as Dynamo® [20], [21] and its linking to Revit Autodesk, or Grasshopper [15] in Rhinoceros, which is implemented as another tool. In addition, another BIM software such as ArchiCAD includes a direct connection with the Python language in its last version (V.24). The new applicability ArchiCAD-Python executes predefined automation scripts, and the own modification and personalisation is possible to carry out automatic tasks [22]. Another important novelty is PARAM-O [23], a visual tool that brings the designer-architect closer to

the Geometric Description Language (GDL) programming, thus easily creating BIM parametric objects without knowing GDL programming.

However, the lack of research studies on the use of the parametric model as a data analysis tool to determine behaviours related to structural deviations caused over time justifies this paper, aiming at advancing in this line. Today the 3D modelling process is composed of several stages in an HBIM project: massive data capture with data acquisition techniques, point cloud post-processing with 2.5D captures, filtering of the point cloud to remove noise and atypical values, and segmentation of the point cloud to classify elements to be later modelled in the BIM digital platform. The next stage is the creation of parametric objects forming part of the model. Under the Revit platform, Dynamo© [24], an open graphical programming software, manages geometry parameters. ArchiCAD does the same with the direct connection and in real time with the Grasshopper programming in Rhino. Rivera et al. [21] used a point cloud and the Dynamo© as a visual programming interface to design the detail of the Royal Cross in the doorway of the Duques de Cadaval Palace in Olivenza (Badajoz). The use of these generative algorithms allows complex geometric forms to be parametrically managed, such as the parametric model of the window in the Camponeschi Palace in L'Aquila (Italy) [25], carried out in an BIM environment. Using complex geometries implies recording the characteristics of the historical architecture. In this regard, the Dynamo© script can also turn the area into a programmed parameter [26] that reflects the mapping of the surface degradation in a 3D model, semantically enriched and supported by the MySQL database [27]. The Dynamo© plugin allows the advanced treatment of the information of the model. Using programming routines based on the Python language, automatic generation actions can be carried out through point clouds [28]. This API interacting with Revit gives many advantages to parameterize the model: the programming of complex geometries, the compatibility of the mesh geometry with Revit, the creation of families, and the potential of connecting ontological knowledge [29]. The geometric modelling could be simplified to basic primitives, called as discretization processes by Bagnolo et al. [30]. This process is developed by modelling a column from the Antas Temple, dividing it into the three functional parts of the element. The methodology of building simple geometric forms with the Dynamo© script is again used in the column from the Brondo Palace (Cagliari) [31]. All these studies showed that generative algorithms allow 3D models with complex geometries to be developed. However, the analysis presented in this study (i.e., the structural analysis of a 3D model though the sequence composed of the point cloud and the parametric model) should also be considered. On the other hand, few research studies have been focused on the wooden structures of a historical building from the 16th century. The behaviour of the wooden trusses that support pitched roofs was analysed with generative algorithms to see the behaviour of the structure [32]. In addition, the Grasshopper algorithm was used, thus automatically transforming the point cloud into a 3D model, and following a workflow, both a truss model and a structural stress analysis linked to Grasshopper were performed with the functions of Dynamo-Revit. On this model representation of the complex geometry in BIM is where the difficulty of its construction lies. Various modelling strategies try that the parametric elements are digital twins. The 3D reconstruction could be generated by interpolating the point cloud into a mesh, thus creating static models with complex surfaces. Moyano et al. [33] used a flow diagram through Rhinoceros and ArchiCad to represent in an A-BIM project the orthostats of the tholos of La Pastora, an archaeological site in Seville. Moreover, Barazzetti and Previtali [34] proposed the use of neural networks through the point cloud for the geometric construction of the surface of vaults.

Great geometric deviations between current models and point clouds could indicate potential errors when processing models [35]. BIM information models by using MDCSs data are being more and more generated in the heritage scope. The reverse modelling process, i.e., from the point cloud to the parametric modelling, is considered in the cultural discussion in the HBIM environment [36], as well as the evaluation of the quality of heritage models in BIM, understood as the potential of informative and geometric content of 3D models [37].

On the other hand, recent studies have shown that BIM digital platforms are completely operative to study structural analyses. Nieto et al. [38] used the laser scanner both to capture architectural pieces and to analyse the deformations in a theoretical HBIM model from a structural point of view. The concept of damage implies a comparison between the current state of the structure and the state of the previous starting point [39]. The starting point could be considered as the theoretical digital model of construction without deformations, and therefore as the starting point of the analysis structure. In addition, the current state would imply the information recording of the reverse engineering process through massive data capture techniques. Structural variations could be captured by BIM operators without applying structural analysis software or other traditional research techniques or methods based on both the direct observation and simplified architectural studies.

From the creation of digital twins, this research work analyses the structural deformations of a portico belonging to the courtyard of a hotel from the 18th century. TLS is used as a time-of-flight sensor, recommended for huge buildings, landscapes or archaeological studies. To avoid occlusions in the 3D survey, the points to be scanned are planned to capture as much geometry as possible. The point cloud is used as a referential auxiliary to survey the model in the BIM platform with the Revit software. Nieto et al. [40] showed that including point cloud data in the BIM software (ArchiCAD and Revit) is essential to contrast the geometric measurements and compare them with traditional techniques. To assess the quality of the model built and to analyse the structural deviations between the parametric model and the actual geometry, Dynamo© is used, and then data are converted to an .xls format. To assess the potential of the method used, structural deviations are measured with the parametric model .stl, and the point cloud in .e57 format with CloudCompare (C2C), a software for data treatment [41]. This dataset shows the capacity of both the techniques mentioned and the BIM parametric models to analyse structural deviations.

The BIM methodology applied to historical buildings should consider the information variables [42], although establishing a Level of Detail (LoD) for historical buildings is not easy [25] as BIM should be related to the documentation process. The HBIM approach of the LoD is characterized by the level of detail as it is a simple or complex example within the construction domain [43]. Thus, the Levels of Development (LOD) where the agents of the process interoperate should be established in the BIM modelling process. LOD is a term referring to the amount of information of the elements that are part of BIM. According to the uBIM guide, LOD levels systematize and unify the degree of reliability of the information in the HBIM model [44]. In this regard, this study has been focused on a LOD 250 approach by defining various surface construction levels, such as cornices and decorative elements, without addressing the internal constructive part of the elements.

3.- Methodology

3.1.- The case study of the Arizón Palace

In the 15th century, the area of the margin of the coast of Cádiz, together with Jerez de la Frontera, was economically developed by the American Conquest. The city of Sanlúcar de Barrameda (Cádiz), located in the mouth of the Guadalquivir river, increased demographically, increasing outside of the primitive wall. The area was increased by the singularity of the maritime trade as the merchants used the harbour in Sanlúcar de Barrameda to start their journeys to the West Indies. The trade development implied an opportunity for rich people as they related to the trade traffic with the American colonies. This development was embellished not just in the urban development but in the construction of architectural sites of historical value. The complexity of the architectural site of the Arizón Palace from the 17th century is only understood by the perception of the trade traffic with America [45]. This architectural site was the house belonging to merchants to the Indies and used for storage; the nobles also lived there. The Courtyard of Honour (see Figure 1) was built between 1721 and 1727. Given the increasing beach tourism, the palace was fully rehabilitated in 1992 and declared of Cultural Interest in 2001.



Figure 1. View of the courtyard of the Arizón Palace: a) Photograph of the Courtyard of Honour in 1989 and detail of the central well; and b) Photograph of the Courtyard of Honour in 2009 at the beginning of the last rehabilitation.

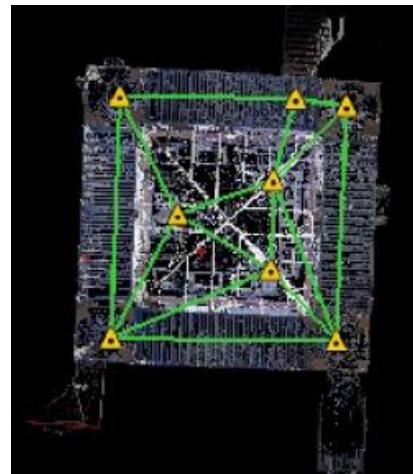
3. 2.- Data Collection

Massive data of the space were acquired with various topographic techniques. The methods based on both images and the 3D laser scanning are the most used in large projects as the old traditional methods, manual methods such as the tape measure or the laser measure, provide many errors. Today the data acquisition technique based on TLS is the most used as it provides accuracy and speed, although other methods based on images have also been used to rebuild 3D models because of their economic advantages, effectiveness [46], and accuracy when modelling CH in BIM [47]. To detect and determine the distance with laser images (LIDAR), TLS differs from operating in an aerial platform. Its methodology is based on calculating the distance between the laser and the object. This procedure is developed by using the time-of-flight method or the wave transmitted and received by the signal [48]. The method scans all the surface area, capturing thousands of points in a coordinate system (x, y, z) and obtaining the point cloud. To know the influence of the geometric variables, topographic tools should be used to measure the accuracy of the solids to be represented. The validity of the model is no more based on the establishment of 3D coordinates (x,y,z) of the GCP, thus guaranteeing that the model is correctly scaled [47]. Together with the laser scanner, the Leica Flexline TS02 total station was used with an accuracy of 2 mm [49] to record the coordinates of the GCP in the

four façades plans of the courtyard. Although the area of the courtyard of the building is not a complex structure, unlike a bridge where the topographic geometry must be deeply studied, the GPC recorded was referenced by points of the total station that provides the other points of the station with a UTM-29S coordinate basis in the WGS 84 system.

Given its compositional wealth, the Courtyard of Honour with porticos in the Arizón Palace was chosen for both the study and the metric-architectural survey (see Figure 2a). A Leica BLK360 laser scanner [50] was used to capture all the geometry of the space. Considering, therefore, that the courtyard provided appropriate dimensions for the scope of 60 range metres, this scanner was used because of its light weight and convenience to be carried. The transversal length of the site analysed for the modelling is not greater than 8.89 metres. In other studies, [51] [52] and [53] used this equipment for greater distances, and [54] showed that the manufacture specifications are averagely fulfilled.

The Leica BLK360 laser scanner uses Waveform Digitising technology (WFD), with a maximum scanning speed of 360,000 points/second. It has three HDR digital cameras of colour sensor



and fixed focal length (simple image 2592 x 1944 pixels, 60° x 45° (v x hz), full-dome scan of 30 images and automatic rectification of space, 150 Mpx, 360° x 300°), as well as an infrared thermal camera (simple image 160 x 120 pixels, 71° x 56° (v x hz), full-dome scan of 10 images, 360° x 70°), the four included in the equipment. The laser system of the equipment obtains a range accuracy from 4 mm to 10 m, and from 7 mm to 20 m.

Figure 2. 3D scanning process: a) Data acquisition for control points; and b) Point Cloud Layout with the equipment position.

The geometry captured by the laser scanner was previously treated, reconsidering the optimal equipment position, so a full scanning could record the spaces of the four sides of the courtyard and its galleries. The itinerary took place regularly to reduce the hidden geometry and occluded points [55], thus obtaining a point density as homogeneous as possible (see Figure 2b). The TLS scanning process was carried out through five placements in the strategic points of the four galleries: corners and access through the stairs, and other three in the courtyard surrounding the central well. The distribution of the equipment implied a distance between the laser scanner and the object from 4 to 7 metres (Figure 3). The “High density” mode was used in all the scans, with a full domo scan duration of 3:40 min, summing 2:30 min

from capturing HDR images. The equipment performance was studied by [56], which confirmed an accuracy of the scanner from 6 mm to 10 metres to record control points.

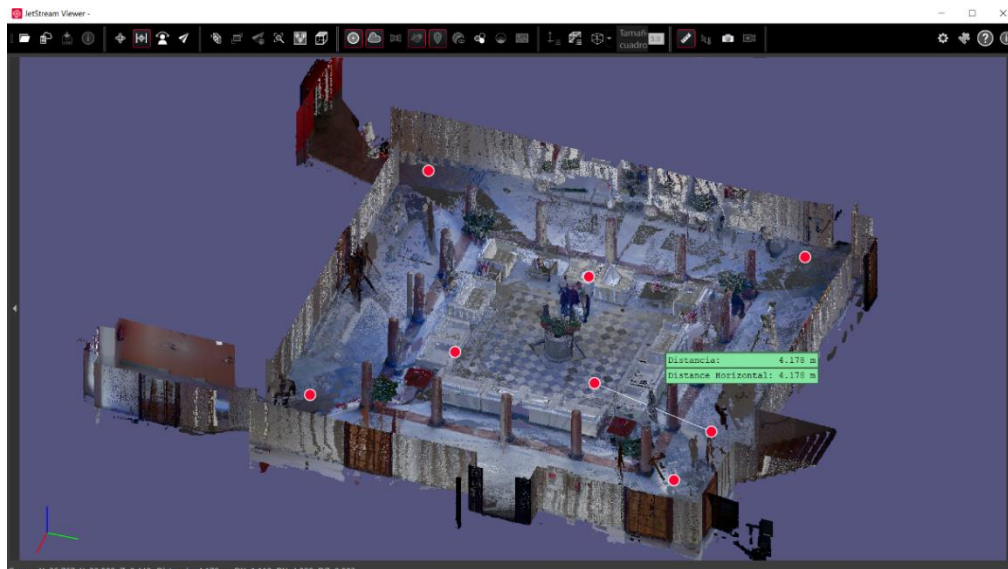


Figure 3. Section/perspective of the Point Cloud with the distribution of the 8 equipment and the distance among them. Visualisation from Leica JetStream Viewer.

After obtaining the records, the adjustment post-processing and cleaning were carried out by the Leica Register 360 software, creating the GPC. Both outside the courtyard and inside galleries, a coupling and alignment of the point cloud were used through effective and accurate procedures, thus keeping an overlay among all positions. A total of eight surveys were conducted at one level, thus fulfilling the goal of covering most of the space of the Courtyard of Honour. The itinerary took place as regular as possible to reduce errors and achieve an optimal point density [57]. A total of 15 links were enough to ensure the scanning coupling (*¡Error! No se encuentra el origen de la referencia.*).

Table 1.- Result of the records with error expression in the placement set.

TLS placements	Number:	Number of connections:	Strength:	Overlapping:	Set error:	Cloud to cloud error:
Level 1 Survey 1	15 placements	43	64%	51%	0.004 m	0.004 m

The recording was carried out through the automatic alignment of the Leica Cyclone REGISTER 360 software, whose alignment resulted in 43 scanning connections among the various point clouds. Finally, a point cloud of 103 million points was obtained for a file size of 10.6 GB in a non-structured format (.e57). Data were also exported to the .pts format of 15.05 GB.

4.- Research workflow

4.1.- Introduction

The action protocol of this research requires clear goals before modelling the heritage assets. Techniques to acquire massive data, such as TLS, were used to fully control the geometry of the objects and the furniture of the historical buildings. The point cloud provides the characteristics and the geometric and chromatic information of the materials [58], the

information related to the visible pathologies [59], the critical areas restricted and dilapidated with the pass of time [3], and a record of image annotation before the 3D reconstruction [60], in which recording could transfer morphological descriptors, such as the occlusion, rugosity or curvature. The first step before including the point cloud in the BIM digital platforms is based on an organoleptic analysis using the information obtained by the MDCSs. In general, old planimetries could be available to be included in BIM and to model theoretical geometries. Today there are software to extract 2D drawings, such as Polyworks® [61], Geomagic® [62] and Geomagic Wrap® [63], among others [7], in which the usefulness of the model is based on obtaining textured polygons and orthographic images. Moreover, VisionLiDAR®, a point cloud processing software [64], processes geometrical plans and export them in the Industrial Foundation Class (IFC) format for the BIM processing. To include both the point cloud in BIM and old planimetries, BIM digital platforms could provide significant data to build the model. The first implementation to include the point cloud is that developed by GreenSipder [65], a plug-in for Autodesk Revit created by Simone Garagnani to reduce the knowledge gap in the computational concept design. Pointools for Bentley [66] accurately modelled regular structures and determined geometric anomalies through TLS [38]. Moreover, Scan-to-BIM shows the great potential of BIM digital platforms to capture the irregular geometry of historical structures. Modelling works are developed by including the full point cloud, as well as through the processes to filter and remove noise and segmentation [67]. It is worth stressing that the point cloud should be manipulated before being included in BIM. In the Autodesk flow, ReCap is available to manage scannings, thus cleaning, organising, and viewing the massive datasets of the point cloud. ReCap Photo is used to create high resolution 3D models with photographs by using the calculation power in the cloud. In other works, HBIM [68] implemented the Scan-to-BIM in a Teamwork flow of ArchiCAD, including range cloud fractions (<280,000 points) after being processed with Cyclone Register 360. Importing the point cloud to BIM is based on segmenting the range cloud and transforming it through the BIM digital platform into a parametric object in the Library Container File (LCF). The point cloud is sectorised by spaces scanned in the church, instead by levels. The virtual monitoring is complemented by the Leica JetStream software as a view tool of the model scanned. The semantic segmentation is a special process to classify elements according to their architectural or artistic category. Nieto et al. [68] worked in a sub-sectorisation of MDCSs data both to structure the identification of movable and immovable assets according to their category and to create a database to record and catalogue the paintings in the Sacristy of the church in Quito (Ecuador).

TLS was used as the data acquisition technique for the experimental campaign, according to the workflow in Figure 4. The point cloud was used as a referential auxiliary to survey the BIM model. Subsequently, to assess the quality of the model built with Revit© Autodesk, the structural deviations between the model and the true geometry were analysed. For this purpose, Dynamo© was used, which creates personalised algorithms to process data and generate geometries. Thus, the building information modelling was increased with the data of an editor of graphic algorithms (core build 2.1.0.7500, Revit© build 2.1.0.7733). The alignment and assessment process were strengthened by the C2C© software.

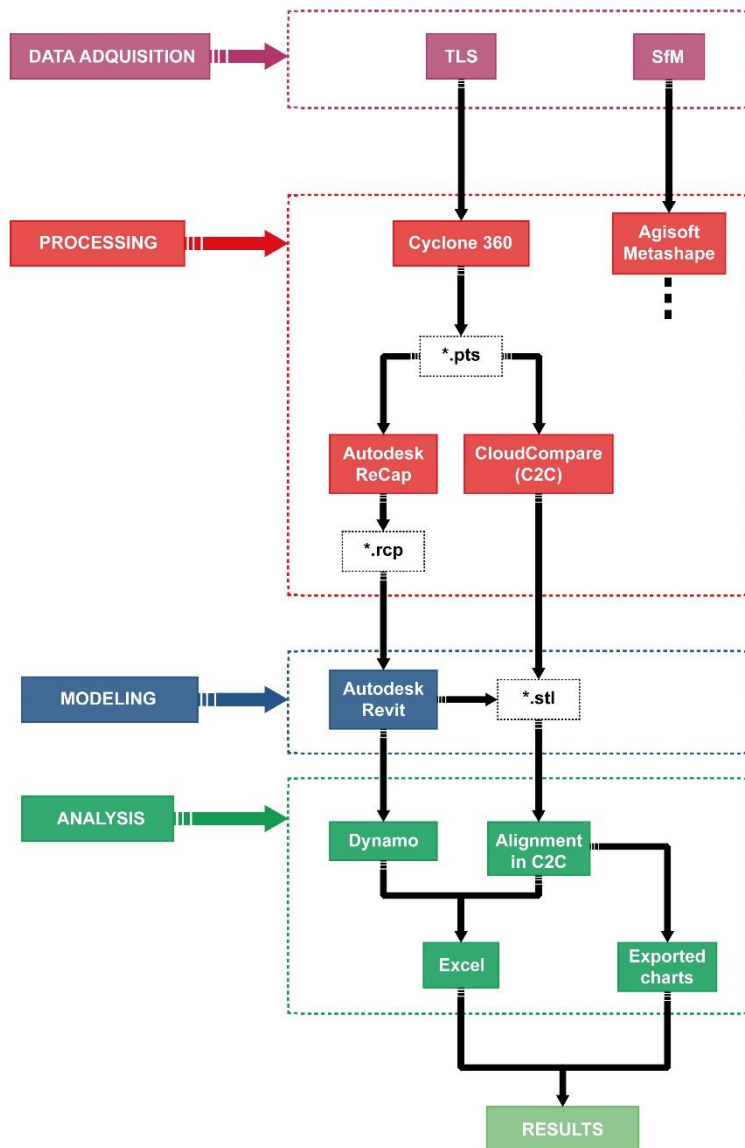


Figure 4. Research workflow.

4.2.- Processing with Autodesk ReCap.

For the modelling, the point cloud was imported to Revit. The point cloud should be edited to align it with the axes (x,y) because this point cloud should work as a 3D referential template for the modelling tasks.



Figure 5. Scanning process.

Next, the project was structured in levels (X1, X2,..... Xn). These levels (see Figure 5) determine the beginning plans of the parametric elements. Defining the referential elements as plans and grills correctly locates the position of columns and arches, being also valid to plan sections. Walls were built through referential plans, and these references are generally used to plan walls: as perfect angles does not take place in comparison with the axes (x,y), it is simplified to avoid errors. The project navigator was organised in a view template because this is an optimal way to organise the modelling. Thus, a Point Cloud Inserts (PCI) is included in Revit, thus managing the valid information in several views within the tri-rectangular trihedron (see Figure 6) that is part of the digital space.

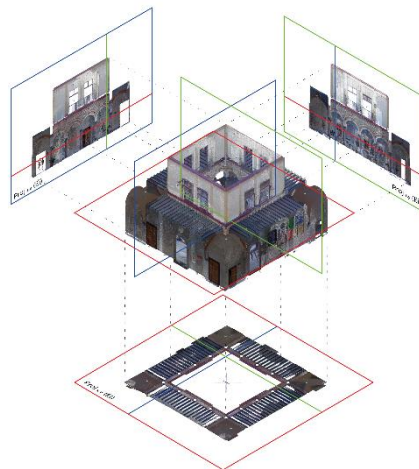


Figure 6. Scanning process.

After obtaining the point cloud and inserted the PCI, it is used to define a set of elements $PCI = \{ E_i \}$, where the surface of each projection in the BIM digital platform of each element $E_i = \{ f_j \}$ is defined by a set of sides f_j . First, an element E_i is orthographically projected from the 3D space in three orthogonal plans ($proj_{x,y}(E_i)$, $proj_{y,z}(E_i)$, and $proj_{z,x}(E_i)$) [69], as Figure 5 shows. Thus, the PCI was obtained in real-time in the digital platform to build the geometric elements.

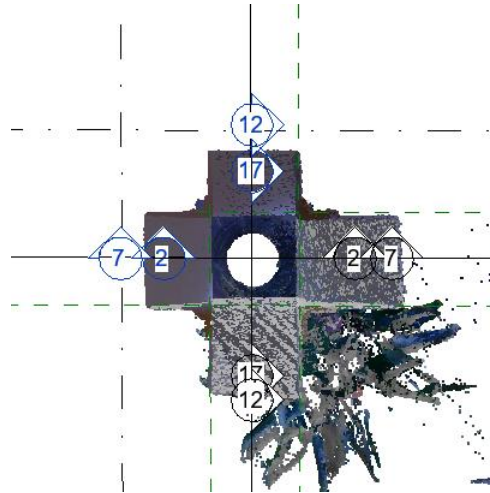


Figure 7. Building layout of the column.

To analyse and assess the quality of the built model by comparing it with the TLS point cloud, the results from the Revit software allowed the point cloud and the construction to be directly seen in various sections and images (see Figure 7). Moreover, 2D drawings could be automatically extracted from the Revit model to make a qualitative control analysis of the dimension variations. To analyse the assessment model, the LOD of the object corresponded to a LOD-250. Although the classification by Caffi et al. [70] was posterior to the definition of the concept of LOD, the basic definitions of LOD, together with a standardised responsibility matrix, were published in the BIM Forum [71]. To analyse the reliability of the model, which was determined by Maiezza [72] as the mean of the levels called Level of Accuracy (LoA) and Level of Quality (LoQ), the quality of the models should be studied [37].

5.- Assessment and analysis of the deformations

Integrating the diagnostic data within an information model is an interesting and important issue in the CH community [60]. Correlating geometric data with teledetection data provides scientists responsible for the CH with a very powerful and useful tool to carry out their tasks. The assessment is analysed, and their observation is recorded and shared with the rest of the scientific community. The double nature in an HBIM model to obtain an ideal model and a set of database that is part of a point cloud determines a unique information about the quality of the model which is being building in the platform and assesses the structural deviations in that moment and in the future when the nature of the elements could change due to the variables in the structures. Macher et al. [73] asserted that including the information about the deviations of the models of TLS data is essential to maintain the actual geometry and to assess the quality of the built model. Keeping and managing many data is possible in BIM digital platforms, so this tool is ideal to establish a structural modelling framework. The first challenge is to avoid a simplification of the model far from reality, so TLD is a database to compare the

model [74]. In this regard, the accuracy level of the model could be assessed over time because it is logic that there are subsequent HBIM models prolonged through the heritage building's life cycle.

For the experimentation analysis, the northern portico modelled in BIM was used (Figure 8a). The modelling analysed the column called C1, and its construction corresponded to the various morphologies of its composition (batten, abaco, frieze, tondino, craft, imoscapo, torus, and plinth) configured in Revit in the ideal "types of family" model. Ornaments in walls were categorised as those in columns. Cornices, recesses, and the ornamental details were built by the *sweeps*, *extrusions*, and the *swept blends profiles*. Ribbed vaults were categorised within generic models, and slabs through floors. Figure 8b shows the result of the full geometry of the courtyard. All the site was composed of various parametric units. The geometry of the model was built through similar processes used in other works on heritage [74,75].

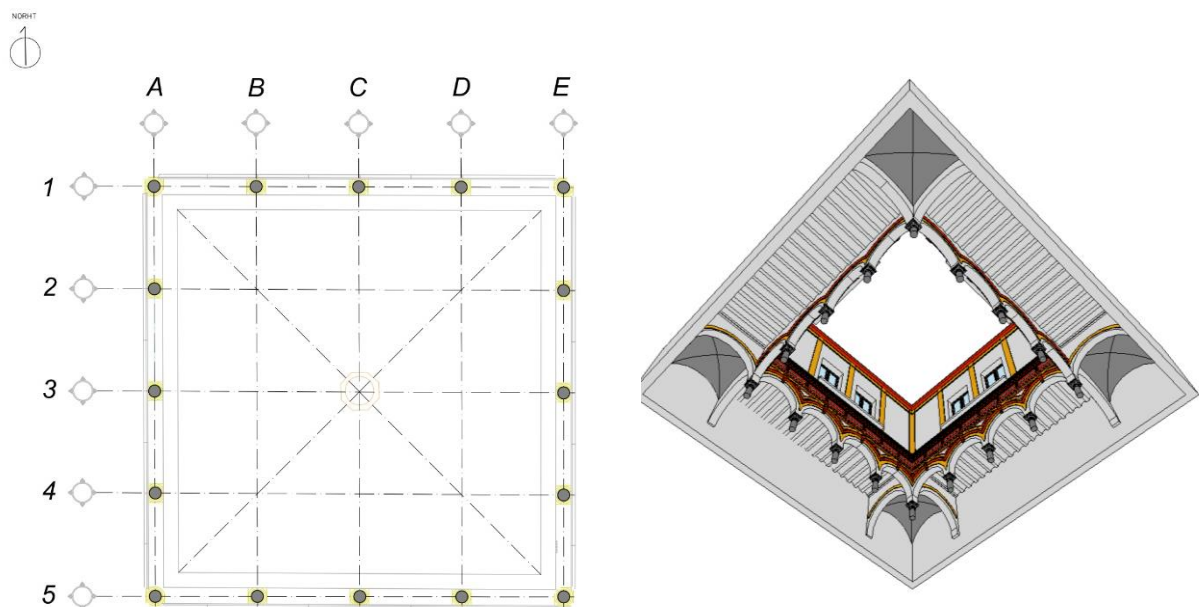


Figure 8. a) Layout plan with grills. The red line shows the location of the portico under study, and b) Perspective of the modelling set.

6.- Geometric information extraction

Most scientific works on HBIM are focused on implementing the grammar of forms through the interactive edition of geometry, using a software or an API such as Dynamo© or Grasshopper; however, the structural analysis has been scarcely addressed, even less using BIM operators and not complex finite element programming software [76]. Thus, the great deal of information that the point cloud included in a BIM model could provide for heritage should be exploited. In addition, the information could be recorded over time, thus showing the static behaviour and the preservation state of columns, arches, walls, and other architectural elements, and as Massafra et al. [32] indicated, converting the model into future monitoring cycles of the displacements and deformations of the structures. Thus, MDCSs could become an interface of a modelling and information system. For some years, Dynamo© has strongly emerged in the visual programming as a methodology of the architectural design. This

tool is ideal to generate complex forms within the new design architecture. Moreover, CH has morphological compositions with complex surfaces, so it gets benefit from this interface. The visual programming refers to the use of a user graphic interface to make and execute sequences of commands. These instructions based on programming codes generate complex parameters forms. This is an open source tool that can be applied in both Revit© and other modelling programmes. In this research, apart from being used in a process to create views, it was also used to analyse the ideal model in comparison with the point cloud through the commands shown in Figure 9.

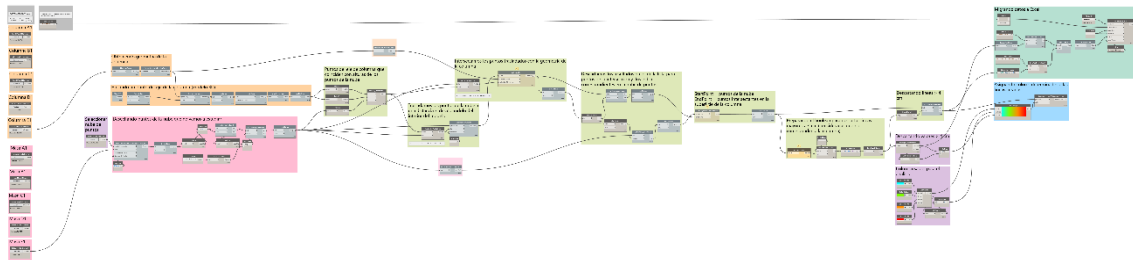


Figure 9. Nodal algorithm developed with Dynamo© and used to acquire deviation data between the point cloud and the 3D model (case study of the shaft of column C1).

The parametric programming carried out by Dynamo©, together with the Steam Nodes package from the version 1.2.4 and Revit, programs and manages the parameters within the families configured in the BIM digital platform. From a series of commands, the data of the distances in the point cloud were exported to the application, and the ideal model to the Excel application. For this purpose, the nodes included by default in Dynamo© and in Steam Nodes were used, such as the node called PointCloud.GetPointsFromBoxSelection (see Figure10).

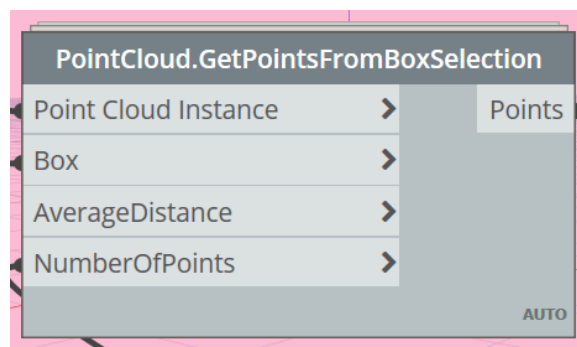
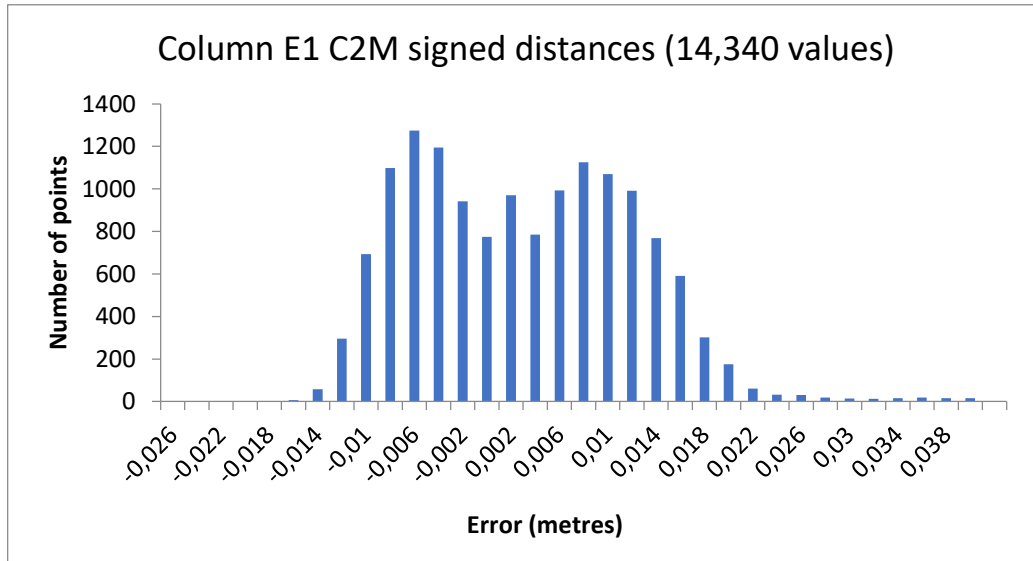


Figure 10. Node from Dynamo©. Steam Noes package.

This node requires a box that segments the point cloud, which is basically a cubic mass with the points of the cloud to be considered in the process. In addition, the segment NumberOfPoints determined the number of points to be considered, also considering the AverageDistance with the value by default (1 mm), previously determined by the operator.

From the data exported to Excel©, a histogram representing the deviation of these points was created.

Table 2.- Histogram of the column E1.



This visual programming tool can visually guide the behaviour and define the geometries through commands for BIM operators. This action takes place in real-time and, with few programming knowledge, a dataset could be obtained by analysing the structural deformations. In addition, as developed in the programming nodes, a colour-scale map could be included, visually determining the deviations between the building model and the point cloud.

To validate the research model in the effectiveness of the study developed with the BIM digital platform through Revit with Dynamo®, the model and the point cloud was recorded within a reference framework through the algorithm of C2C®. The experimental sample included three architectural elements built in the general model of the Courtyard of Honour in the Arizón Palace. Thus, the independent column C1 could be studied. In this column, the geometric quality of the construction of the shaft and its respective morphological elements of base and capital can be determined. In addition, the column and a part of the arch could also be studied to analyse the structural deviations between these two elements. Their comparison could determine whether the quality of the built model is adjusted to reality, as well as the fundamental variations. Finally, the northern portico was fully studied, establishing the total deviation and levelling values of the model.

C2C® has been widely used to compare the point cloud obtained with SfM, taking TLS as a model: Georgantas et al. [77] used TLS as a reference to compare the IBM photogrammetry through C2C®; Teza et al. [78] compared TLS and SfM to determine a morphological analysis in terms of differences. C2C® was also used to analyse the image reconstruction algorithms obtained with Agisoft and Open Computer Vision (CV) [79]; Koutsoudis et al. [80] analysed the average distances and the standard deviations of all the single-view range scans in comparison with the mesh; and Moyano et al. [33] compared the construction of BIM parametric objects belonging to complex archaeological forms with the point cloud data from the TLS to assess the modelling. In addition, Robles et al. [81] analysed the verticality of the Bayacas bridge in Órgiva using CloudCompare® software to compare the point cloud with a vertical plane. A similar method was experimented by Nieto et al. [82], who evaluated the deformation of a roof beam of the Pavilion of Charles V by overlapping the point cloud and the HBIM. Used as a reference, the point cloud was figuratively a photograph of the damaged area. Moreover,

textual markers ('Marker' tool in ArchiCAD®) were incorporated alongside parametric objects to indicate structural elements affected by water seeping. Andriasyan et al. [15] analysed the study between the model and the point cloud of Scan to BIM in the courtyard of the Pilatos Palace in Seville. Makupa et al. [83] showed both the importance of the TLS to detect structural changes and to monitor deformations and how the M3C2C algorithm developed by [84] should be used as a comparative method for deformations.

To compare the building model in BIM with the point cloud of the TLS, the total point cloud was worked with 107 million points in a non-structured format (.pts) and including it in C2C© to segment it in three parts: column C1, set of column and arch, and northern portico. After the segmentation, noise was filtered and cleaned according to the parameters established by Girardeau [41], resulting in three point subsets with a structured-binary format (.e57). The segmentation was manually carried out, and part of the data subset segmented with the HBIM model was included in the software in the .stl format Polygon fencing in software CloudCompare© Version 2.10-alpha [85], which removed noise, non-related points and non-desirable elements, such as seats placed in the middle of the courtyard, floor lamps, and flowerpots.

After obtaining the point subsets of the point cloud of the segmented TLS, the HBIM building model was aligned with each part (see Figure 10) through the pairs of points selected (see Figure 11) which are common between the .stl model and the .e57 point cloud. The six pairs of points (northern portico) (R0-A0, R1-A1, R2-A2, R3-A3, R4-A4, and R5-A5) were located in the capitals and the base of the intermediate columns, with errors of 0.015, 0.017, 0.016, 0.015, 0.011, and 0.014 respectively, and an RMS of 0.01542 m. The co-recording or recording was applied with the Iterative Closest Point (ICP) algorithm, implemented by CloudCompare M3C2 and created by Lague et al. [84] to optimise the alignment automatically. The results of the series of the three point subsets are included in Table 3.

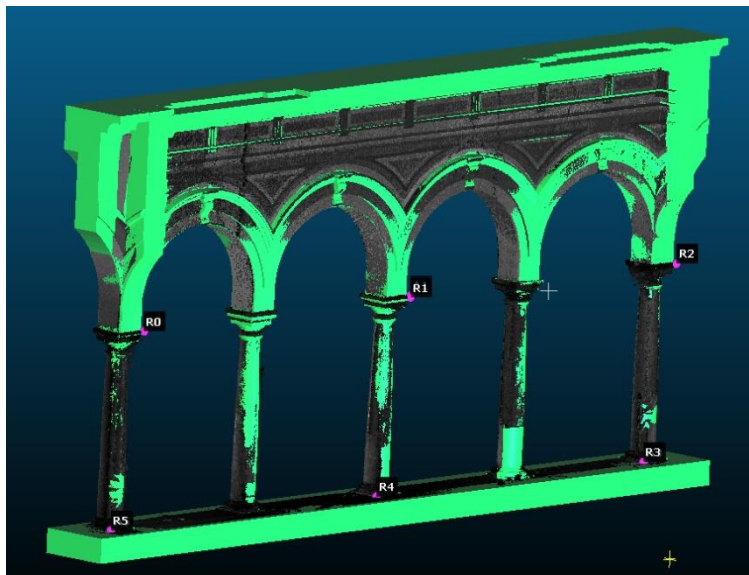


Figure 11. Alignment of the point cloud of the northern portico, and the 3D model extracted by Revit.

Table 3.- Results of the RMS of the alignment between the parametric model and the point cloud.

RMS of the alignment between the parametric model and the point cloud in C2C©			
	Column C1	Set of column and arch	Portico
RMS	0.0076	0.0061	0.0154

Thus, the distance between the model and the subset of partial points of the segmented portico was calculated. The parameters studied were the Root Mean Square Error (RMSE) according to Equation 1, the minimum and maximum distances between the model and the point cloud, the average distance, the standard deviation, and the estimated error in metres. The deviation between the digital twin model and the actual geometry presented two characteristics: the high presence of points in the zero value in comparison with the other distance intervals, and the high standard deviation that could be calculated through the equation already mentioned by Arias et al. [86]:

E.1

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

Where:

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

To validate the programming of the deviations obtained with Dynamo©, the frequency of atypical Gauss values was also analysed. This frequency showed the statistical approach of the behaviour of the point distribution according to Equation 2.

E.2

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Where:

- σ = standard deviation
- σ^2 = variance
- μ = mean
- π = Pi number
- e = Euler number
- Y = height of the curve for any value of x
- x = value in the horizontal axis

The frequency data distribution with respect to the height and the deviations in metres were estimated with a Gaussian function density, with a bandwidth of 10.

7.- Results obtained in the geometric assessment

7.1.- Results from the interpretation of the deviations with Dynamo©

Under the dataset provided by Dynamo©, the parameters studies were those correlated to the direct data emitted by the use basis of the M3C2C algorithm. These parameters were as follows: the minimum distance, the maximum distance, the average distance, and the standard deviation. After exporting data from Dynamo© to a structured format (.xls), data were treated to obtain the parameters according to the results included in Table 4.

Table 4.- Average distances and standard deviations of the single-view range scans compared between the building model and the point cloud (in metres).

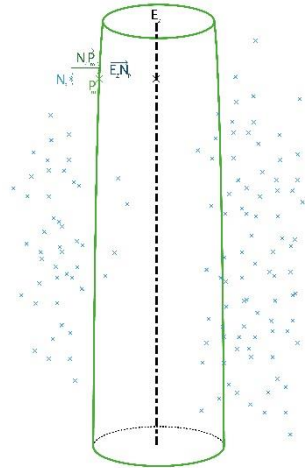
Average distances and standard deviations of the single-view range scans compared between the building model and the point cloud (in metres)				
Survey A (Dynamo©)	Standard deviation	Min. Distance	Max. Distance	Average distance
Column C1	0.0074	0.0000	0.0396	-0.0033
Set of column and arch	0.0407	0.0000	0.1906	0.0265
Portico	0.0446	0.0000	0.5520	0.0109

7.1.1- Analysis of the column

For the working process using the code of the nodal algorithm created, after included in the Dynamo environment, the execution of the algorithm was changed from automatic to manual to avoid keeping an unfeasible code in an automatic execution. The “Select Model Element” node was used to select the column to be studied, the prismatic mass previously created, and the point cloud. Through the *Element.Faces*, the “column” element was turned into a geometry interpreted by Dynamo©, and then an axis point (P_E) of the resulting geometry was obtained. On the other hand, the point cloud was segmented by using the prismatic mass and decimated by the user. The resulting set of points was called N_p . This process implied that the selection was like the segmentation of a point subset within the decimated point cloud. Coordinate Z was removed from P_E , maintaining the coordinates X and Y. Coordinates Z were extracted from N_p and coupled with $P_E(x, y)$, thus obtaining points both in the axis of the geometry and in the point cloud. These points created on the axis of the geometry were called E_z'' . The vector $\overrightarrow{E_z N_p}$ was created, and following the direction of this vector, the points of N_p were transferred to a distance that ensured that none of these points was within the geometry (N_p'). The vector $\overrightarrow{N_p E_z}$ was created, and following its direction, the points of N_p' were projected on the geometry. Through this process, the nearest point of the 3D model to its respective neighbour of the point cloud was determined. This point set on the 3D model was called P_m . A line with the points of N_p and P_m was created, and their length were extracted, which coincided with the absolute minimum distances between the point cloud and the 3D model. To determine the negative distances, or in other words, the points of N_p within the model, the vector $\overrightarrow{N_p P_m}$ was created, and the mathematical condition was imposed according to Equation 3:

$$Distance = \begin{cases} +, & si \left| \overrightarrow{E_Z N_P} \right| > \left| \overrightarrow{N_P P_m} + \overrightarrow{E_Z N_P} \right| \\ -, & si \left| \overrightarrow{E_Z N_P} \right| < \left| \overrightarrow{N_P P_m} + \overrightarrow{E_Z N_P} \right| \end{cases}$$

Figure 12 graphically represents the vectors to which the mathematical condition of Equation 3 refers, and Figure 13 shows the code of the nodal algorithm executed on the 3D model of the



column C1 of the portico. The colour gradient was applied to the lines obtained in the nodal process.

Figure 12. Graphic representation of the code process of the nodal algorithm.

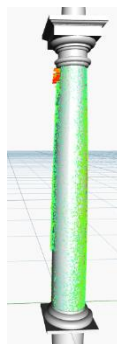


Figure 13. Parametric modelling of the central column of the northern portico.

Table 5.- Histogram of the column C1 (Dynamo©).

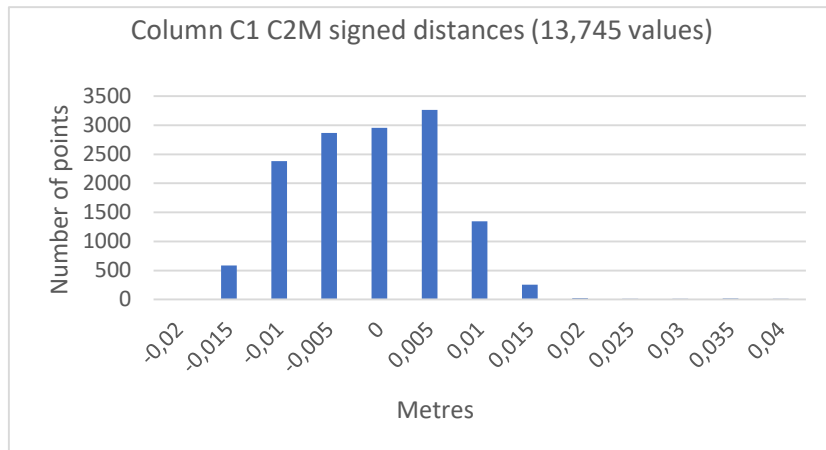
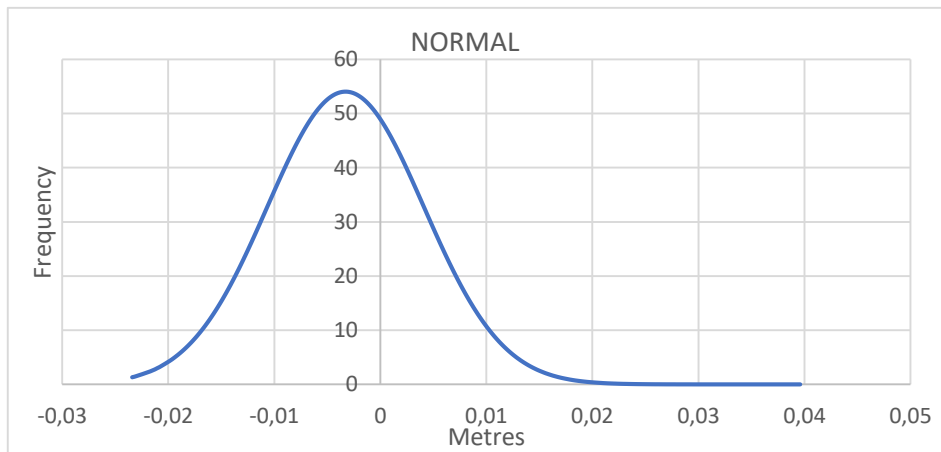


Table 6.- Graph of the normal deviation of the column C1 (Dynamo©).



The column image showed that there were certain residual values (see Figure 13) corresponding to the point cloud being part of the flowerpots, and the graph included in Table 2 shows that approximately 80% of the sample points were between -0.01 and 0.01 m. Thus, there was no systematic influence within the algorithm, and the deviations were not significant. Table 6 shows a deviation tendency of -0,004 m in the point cloud in comparison with the 3D model. In the analysis, the negative values corresponded to those points within the model, and the positive were outside the model in both sides.

7.1.2.- Analysis of the set of column and arch.

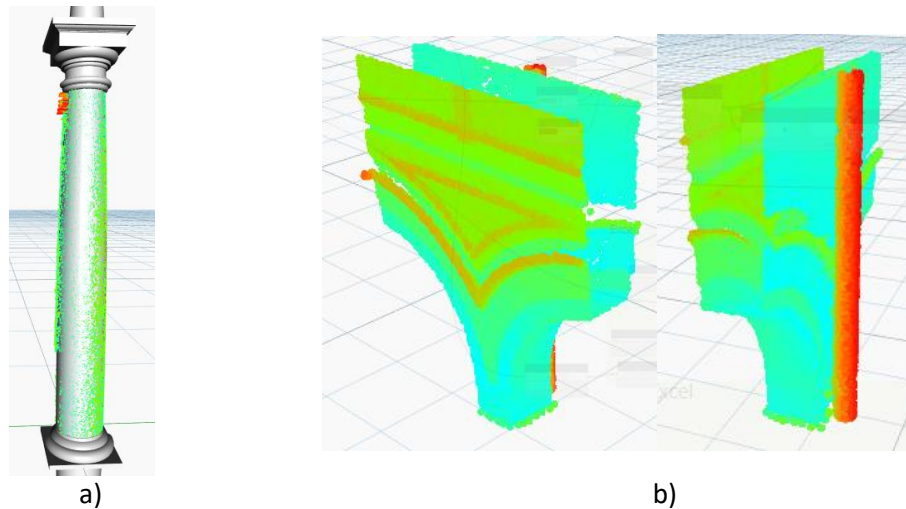
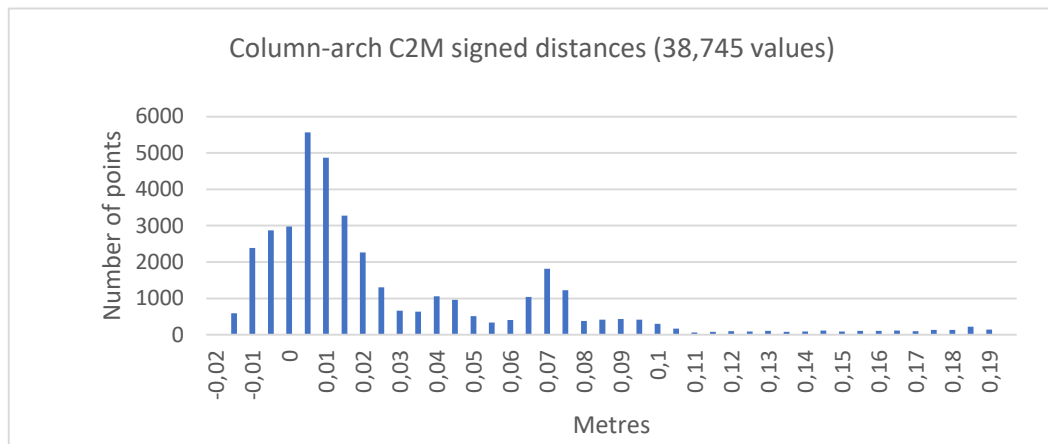


Figure 14. a) Parametric modelling of the column C1, and b) beginning of the arch of the column C1.

In this case there were also atypical or residual values in the analysis, such as the case of the values corresponding to the drainpipe found in the segmentation of the arches. The reason was that the point cloud could not be accurately segmented within Dynamo®.

Table 7.- Histogram of the set of column and arch.



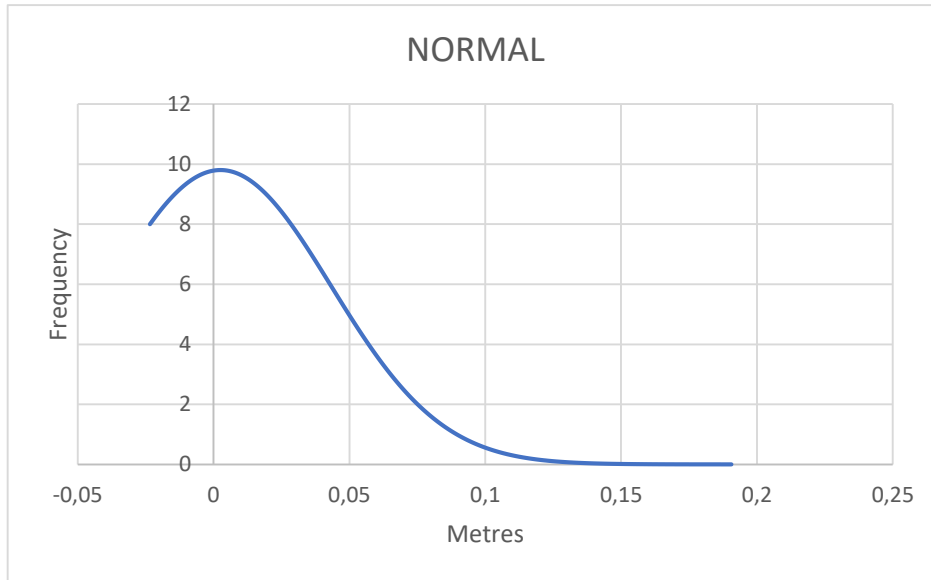
Unlike the previous case, Table 7 shows the existence of significant deviations from the value of 0.020 m. These values were the result of the external elements of the assessment model, and therefore they were residual values.

As Figure 14b shows, the points with the greatest deviation in comparison with the model studied corresponded to the drainpipe, and the proportionality of these residual values in comparison with the values corresponding to the model studied was greater than in the previous case.

Moreover, this increase from the value of 0.055 m took place because the ornaments of the wall were not considered in the 3D model; the flat sides of the wall were only considered. In

the graphic result of the normal deviation (Table 7), the average of the deviation was virtually 0.

Table 8.- Graph of the normal deviation of the set of column and arch (Dynamo©).



7.1.3.- Analysis of the column portico

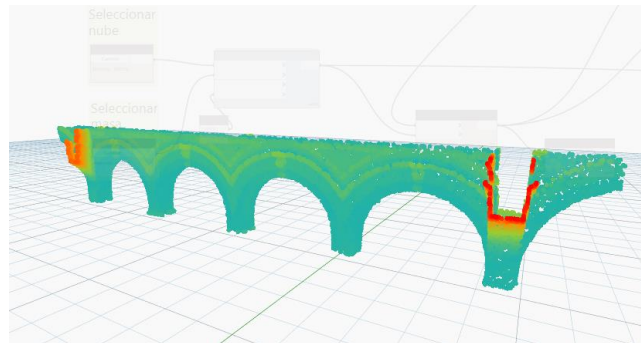


Figure 15 Parametric modelling of the northern portico.

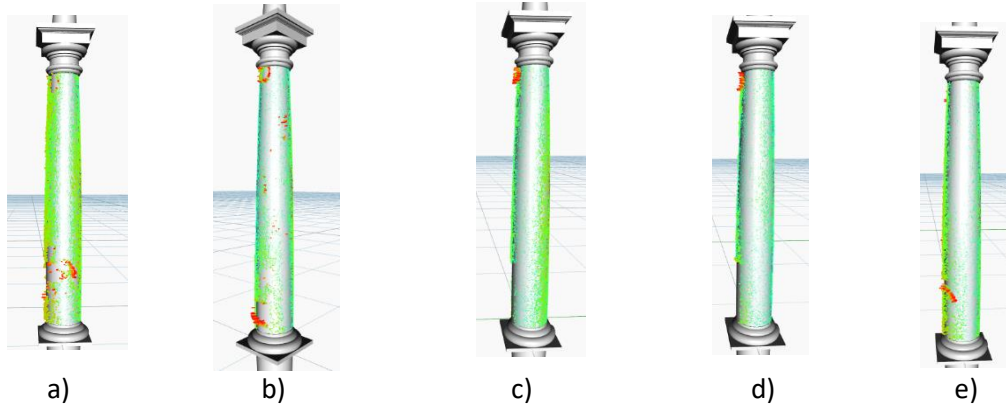
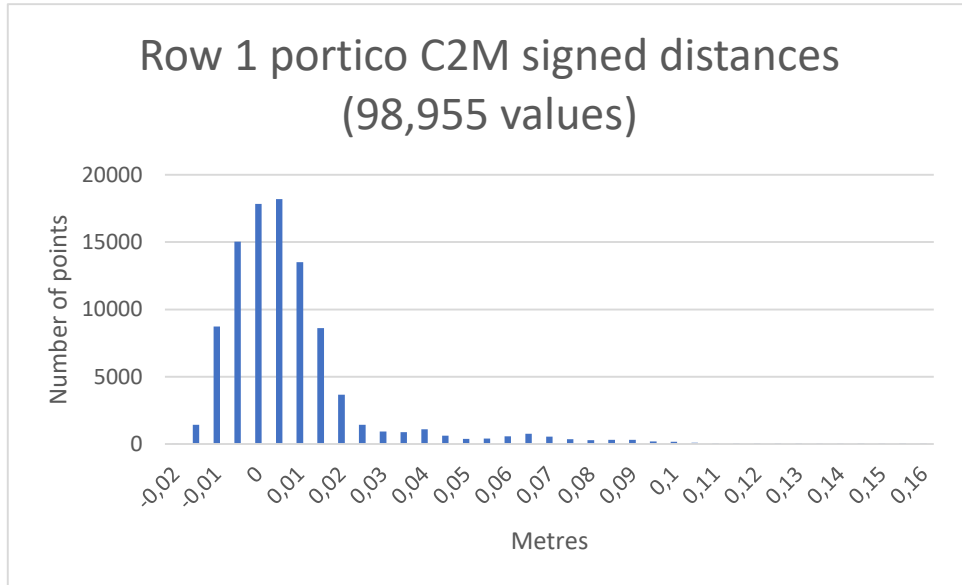


Figure 16. a) Column A1, b) Column B1, c) Column C1, d) Column D1, and e) Column E1.

As expected, this case also obtained residual values; however, the segmentation was greater, so the proportionality of these values was not so significant as in the previous case.

Table 9.- Histogram of the northern portico of the Courtyard of Honour.



There was also an increase from the value of 0.055 m, but it was lower than in the case of Table 7. In addition, almost all points were between -0.01 and 0.02 m.

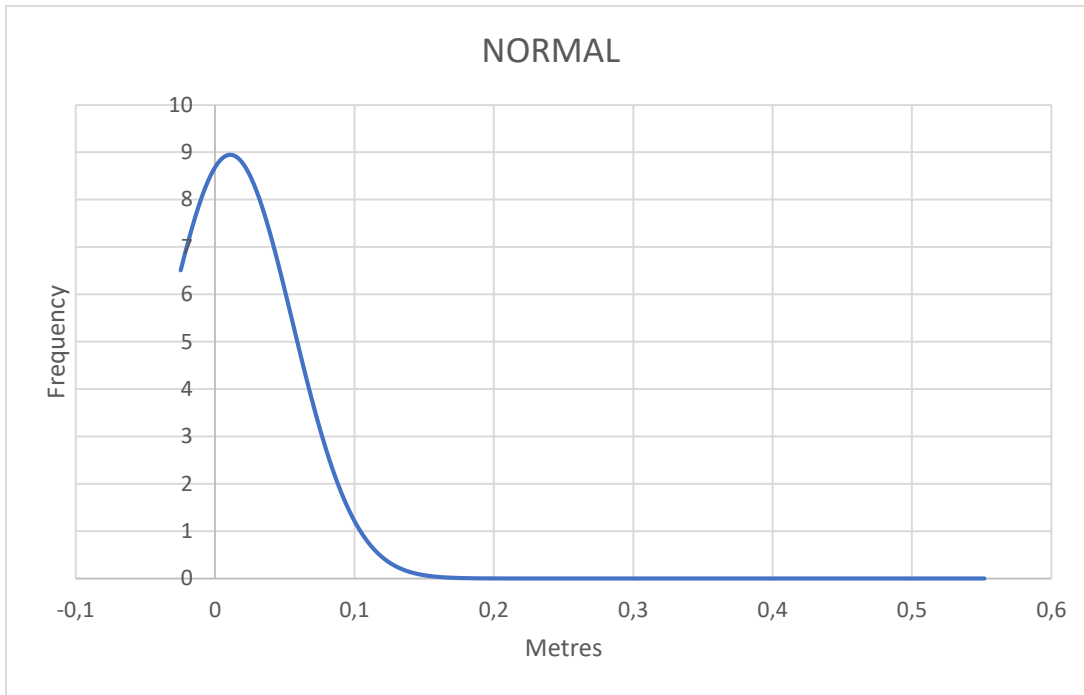


Table 10.- Graph of the normal deviation of the northern portico (Dynamo©).

7.2.- Results from the interpretation of the deviations with C2C©

Under the dataset provided by C2C©, the parameters studies were those correlated to the direct data emitted by the use basis of the M3C2C algorithm. These parameters were as follows: the minimum distance, the maximum distance, the average distance, and the standard deviation. The difficulty presented by the point cloud post-processing in both BIM and another platform was the file extension. For instance, ArchiCAD® Graphisoft presented a limit of 14 MB, which is overcome in Revit® Autodesk by the workflow with ReCap. In this case, the cloud was processed through the Cyclone Register 360 software and was exported to an interchange format (.pts) to maintain the filtering and the segmentation applied. Cloud Compare is a software for point cloud processing and is capable of segmenting and filtering, but the size of the .pts file (14 GB) slows down the work. From the respective segmentation of the point subsets, they were kept in non-structured files to be compared between the 3D model and the point subsets being part of the column C1, the set of column and arch, and the portico. Table 11 shows the data obtained by following the parameters described.

Table 11.- Average distances and standard deviations of the single-view range scans compared between the building model and the point cloud (in metres).

Average distances and standard deviations of the single-view range scans compared between the building model and the point cloud (in metres)						
Survey B (C2C©)	Standard deviation	Min. Distance	Max. Distance	Average distance	RMS	Estimated standard error
Column C1	0.0092	0.0000	0.0668	0.0087	0.0076	0.0092
Set of column and arch	0.0185	0.0000	0.1146	0.0115	0.0061	0.0204
Portico	0.0201	0.0000	0.1608	0.0540	0.0154	0.0402

7.2.1- Analysis of the column

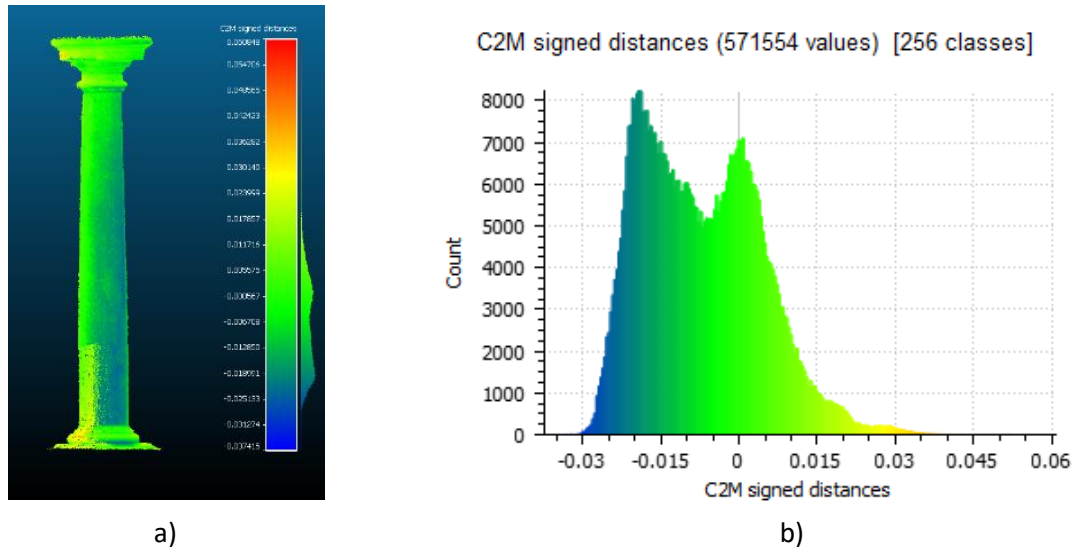


Figure 17. a) Column A1, and b) Histogram of the column C1.

According to data from the results in Table 11, there were many points at a distance between -0.015 and -0.02 m from the 3D model, although there were also many points at a distance close to 0.00 m. A total of 53% obtained deviations between -0.20 and 0.05 m. The dispersion between the model and the point cloud was very significant, with many points exceeding 0.015 m.

Like in the previous methodology, most point clouds were around -0.01 and 0.01 m, but in this case, the number of samples used for the analysis was greater, i.e., 571,554 samples in contrast to the 13,745 samples of the case studied in Dynamo©.

7.2.3.- Analysis of the set of column and arch.

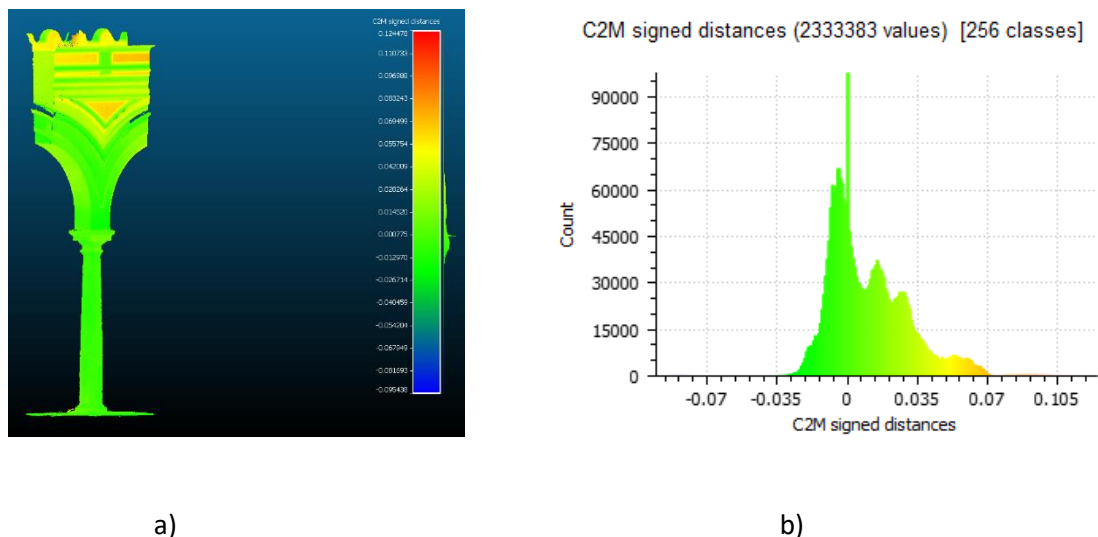


Figure 18. a) Column A1, and b) Histogram of the column C1.

Unlike the results obtained in the previous methodology, in this case the results showed a greater percentage of points between -0.10 and 0.05 m, and the remaining determined

atypical values. The scale of histograms was constant in the axis of abscissas to ease the understanding. The value of the zero deviation in the axis of abscissas represented the correspondence between the objects compared: the 3D parametric model and the point cloud [14]. Thus, this was the interval in which the distance between both objects was null.

Table 11 also shows the strong tendency in the distance of 0.00 m, which could be interpreted as both an accurate alignment and a minimum deviation of the structural elements in this segmentation.

7.2.3.- Analysis of the set of column and arch

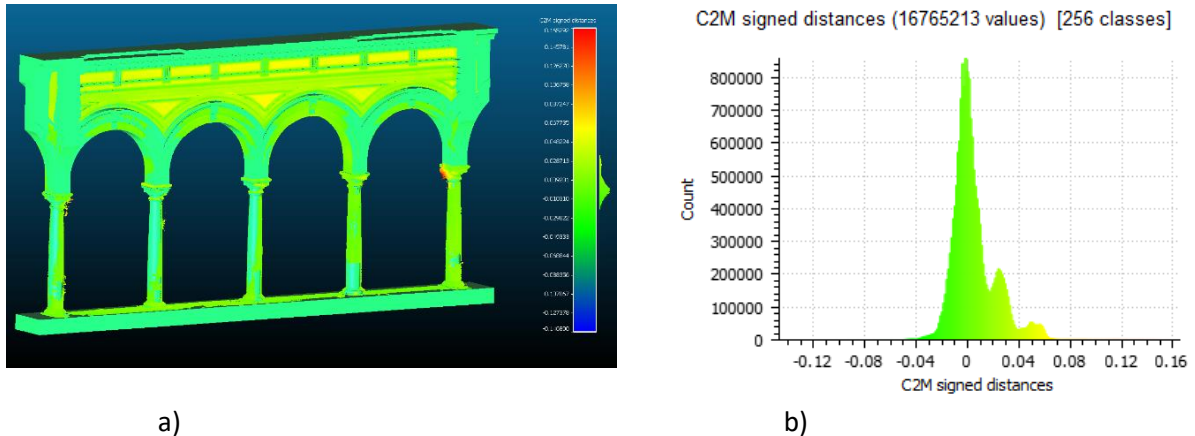


Figure 19. a) Column A1, and b) Histogram of the column C1.

In this segmentation, the deviation in the structural elements was minimum. Table 11 also shows the strong tendency in the values close to 0.00 m. There were atypical values belonging to the flowerpots placed next to the right column (corresponding to the column E1).

In the ornaments of the walls in Figure 15, there was a colour pattern repeated in the other cases in both methodologies. This section presented a slight deviation in those areas corresponding to the exposed side of the wall, so it was understood that the wall was expanded in the upper part of the arches. This point deviation due to the expansion of the wall could explain the plateau in Tables 10 and 11 from the value 0,035 m, a slight plateau in Table 6 (probably because of the number of samples used) and less uniform in Table 4.

8.- Reliability of the results obtained in the methodologies

The working process was different in both methodologies. Dynamo© is a visual programming software and not a programme to analyse deformations, although [32] used a projection algorithm to assess and interpret the deformation data of architectural elements. Moreover, Yang et. al [87] transferred parametric data from Dynamo© to the structural analysis software COMSOL. Dynamo© works in the same working space with the model and the point cloud, so a preadjustment or coupling is not required. This working space (x_i, y_i, z_i) is related to the object, so that they are well coupled in their set when the segmented portions are included.

Dynamo© decimates the point cloud to reduce the number of points and the amount of information, thus working more quickly. The information lost is proportional and data are therefore representative. In contrast, C2C© works with all the points, so the ordinate axis has different values in the various histograms. In the configuration process of the algorithm there

were some difficult issues to be addressed, such as the interpretation of some geometries of the details of the capital. When obtaining the intersections required to calculate the distances, some geometries could not be interpreted, so the analysis was based on the deviation of the shaft. In the case of the walls, the assessment of the details of the cornice was not required in Dynamo©. One of the advantages of this algorithm is that the set of the point cloud should not be segmented, as in C2C©. In the same platform, the element to be compared was selected, and the number of points was limited through a cubic mass. In general cases, atypical values not filtered previously were included. Unlike Dynamo©, C2C© is a programme to process point cloud, whether from TLS or SfM, whose advantage is the comparative analysis among clouds, models and meshes. C2C© works outside the Revit environment, so more powerful hardware is required according to the characteristics (Table 12) of the equipment used in this research.

Table 12.- Characteristics of the hardware used in the two methodologies.

Characteristics of the hardware used in the two methodologies	
Dynamo©	CloudCompare© (C2C©)
Windows 10 64 bits	Windows 10 Pro 64 bits
8 Gb RAM	32 Gb RAM
Graphic card NVIDIA GeForce 920M	Graphic card NVIDIA GeForce RTX 2080 Ti
Processor Intel Core i7-4712MQ 2.30 GHz	Processor Intel Core i9 -10900K 3.70 GHz
4 cores	10 cores

Table 13 shows that both methodologies had the same behaviour, except their error bars, in which atypical values took place. Both methodologies shared a similar proportionality among their quartiles.

The most important difference took place in the set of column and arch of the Dynamo© methodology, where the range bar Q2-Q3 was greater than the other cases. The reason could be that the points of the drainpipe (see Figure 3) could be included in the quartile Q3.

C2C© was specific for this task, so data obtained through that methodology were more effective. By comparing these data with those obtained through Dynamo©, and analysed with Excel©, there were similarities enough to consider the methodology used by Dynamo© reliable.

Table 13.- Diagram of the data obtained by quartiles.

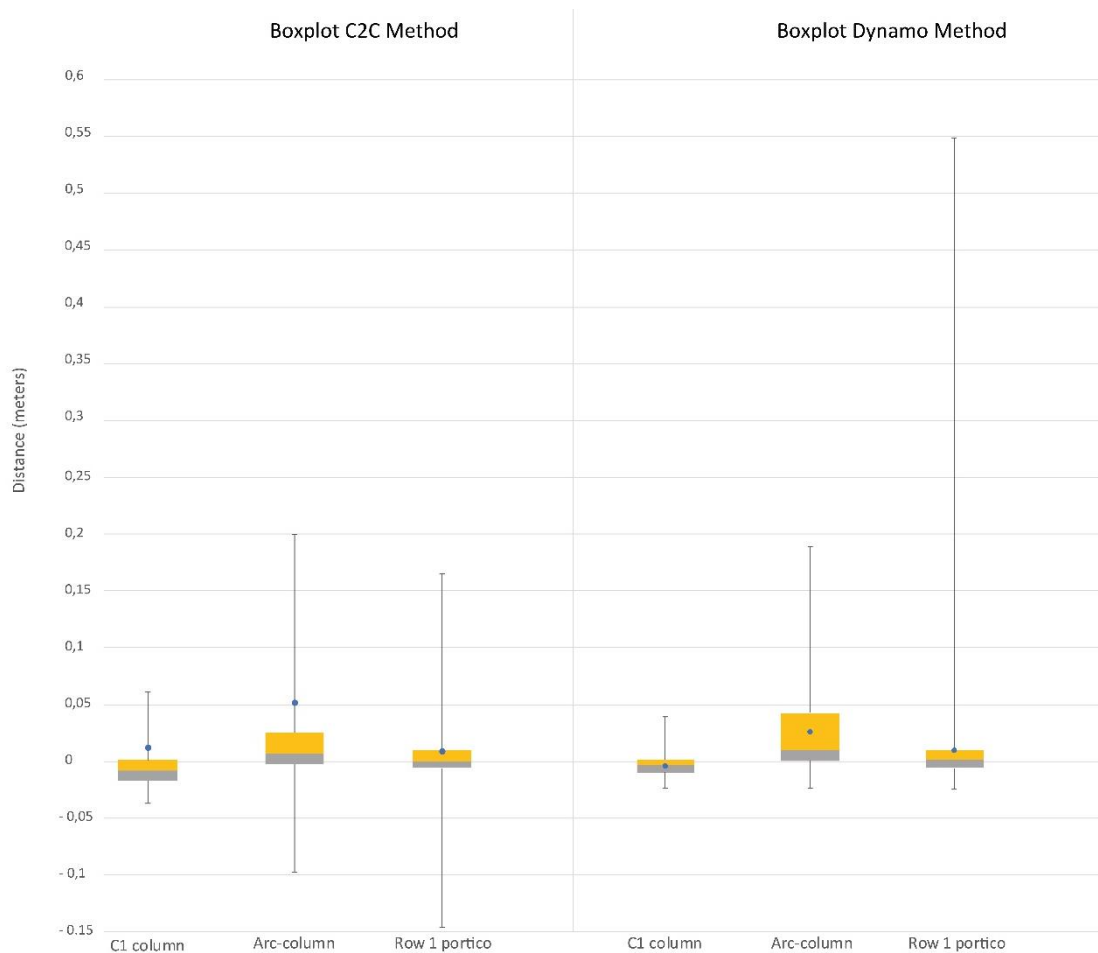


Table 14. Statistical data from C2C©

C2C© data			
	Column C1	Column-arch	Row 1 portico
MIN	0.037415434	0.097015187	-0.14688988
Q1	0.017455767	0.002934112	0.006651728
Average (Q2)	0.008627452	0.006357846	0.000554417
Q3	0.000584702	0.024941762	0.009201281
MAX	0.060463703	0.199165976	0.16407298
Average	0.011907975	0.051075394	0.00859155

Table 15. Statistical data from Dynamo©

Dynamo© data			
	Column C1	Column-arch	Row 1 portico
MIN	-0.0234	-0.0234	-0.0247
Q1	-0.0092	0.0008	-0.0051
Average (Q2)	-0.0031	0.0102	0.0016
Q3	0.0021	0.043	0.0098
MAX	0.0396	0.1906	0.552
Average	0.003275198	0.02654251	0.010867552

The evaluation of the quality of the parametric model built in comparison with the TLS point cloud allows a direct view in various transversal sections or plans. They are geometric studies from geometral plans. To show an architectural analysis distinguished by the section plans, the parametric model and the point cloud obtained with the laser scanner, variations could be determined in Figure 20. These measurements could reach differences of up to 0.0630 metres.

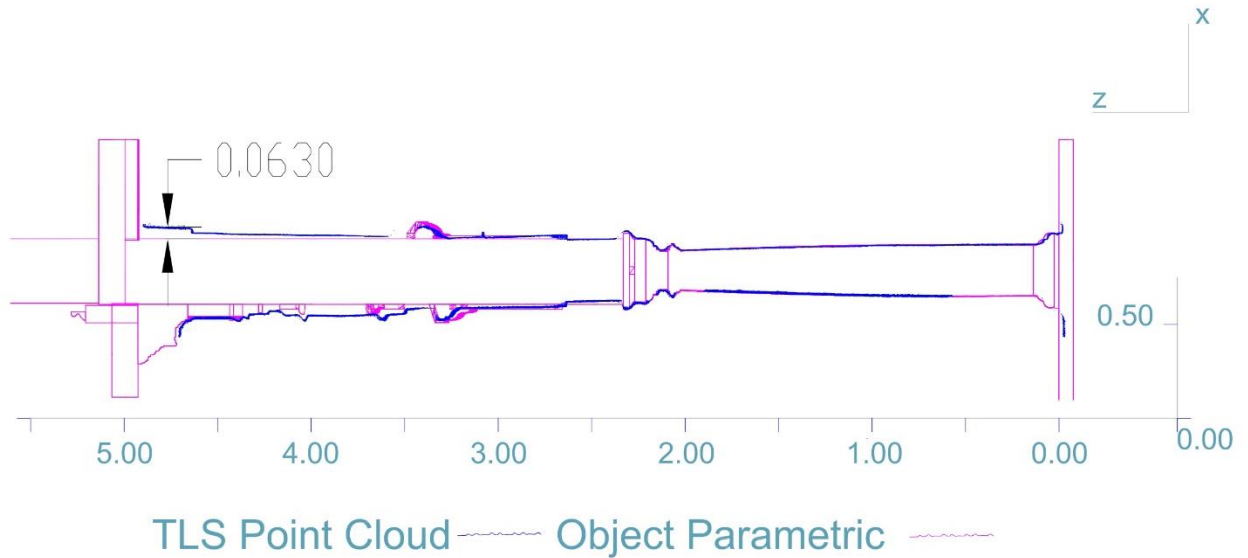


Figure 20. Architectural information and analysis through transversal plans between the parametric model and the TLS.

9.- Discussion of the results

After analysing the integration of the data obtained by both methodologies, the deviations between the 3D model and the point cloud were determined. The technique used belongs to the data acquired by the TLS, in which displacements and structural alterations could be interpreted. The behaviour of the brick manufacture could also be analysed, and how it was altered according to the evolution of the life cycle. The results showed asymmetric measurements in comparison with the vertical plans forming part of the 3D reconstruction model. Table 13 shows that the average value (represented with a blue point) was not an actual analysis value due to the existence of atypical data. Data between the quartile 25 and 75, also called interquartile range, represented the values considered typical, and according to these values, the deviations in the column C1 were shown. Data from Table 14 oscillated between -0.0018 and 0.001 m, with an average of -0.008 m. Thus, the dispersion of the cloud in comparison with the 3D model was balanced, i.e., based on the average, there was the same point concentration at a distance of ± 0.009 m. According to data from Table 15, the interquartile range was between -0.009 and 0.0021 m, with an average of -0.0031 metres. This implied that, based on the average and at 0.0055 m, there was the same point concentration. In the case of the set of column and arch, the interquartile range in Table 14 was between -0.003 and 0.025 m, with an average of 0.006 m. This implied that the data concentration between Q1 and Q2 (with a length of 0.009 m) was greater than in the range Q2 and Q3 (with a length of 0.019 m); thus, data from the range Q2-Q3 were less solid than data from the range Q1-Q2 or, in other words, the actual deviation values between the 3D built model and the model of the point cloud generated by the TLS were obtained in the range Q2-Q3. This also occurred in Table 15, although with a greater dispersion in the range Q2-Q3, with a length of 0.03 m in comparison with the range Q1-Q2, with a length dispersion of 0.009 m.

In the analysis of the portico, Table 14 again shows a dispersion difference between Q1-Q2 and Q2-Q3, with a dispersion of 0.006 m and 0.0098 m, respectively. The dispersion difference between ranges was less than in the previous case, but it provided an essential datum: the solidity of the general deviations between the model and reality, with an average very close to

0.000 m, and with actual general deviations within 0.01 m. This tendency in the differences between the ranges is again shown by Table 15.

With this analysis, the systematic error was determined, whose value was 0.01 m, so it was an acceptable systematic error, i.e., the quality of the 2D model in comparison with reality was acceptable.

Heatmaps or colour scale were therefore required to correctly interpret the deviations of the construction elements. Without these heatmaps, the results would be less operative and visual. By comparing the heatmaps generated with Dynamo®, it was concluded that better results were obtained when the segmentation used for the analysis was lower because, by decimating the cloud to 25,000 points in a lower section, there was a greater point concentration than in the portico (see Figures 3 and 4). In the case of the heatmaps generated with C2C®, that heat range was shared, thus easing the interpretation of the results.

This algorithm was also used to analyse the deviations of the arches (whether partially or totally) and to see these differences in the chromatic scale. The differences of the points could be determined as the height of the wall increased, indicating that this side was expanded in the upper part and, according to the colour gradient in Figure 12, this deviation went from 0.035 to 0.07 m.

Table 16.- Characteristics of the hardware used in the two methodologies.

	Data dispersion between the median and the quartiles					
	C2C®			Dynamo®		
	Column C1	Column-arch	Row 1 portico	Column C1	Column-arch	Row 1 portico
Q1-Q2 =	0.0088	0.0093	0.0061	0.0061	0.0094	0.0067
Q2-Q3 =	0.0092	0.0186	0.0098	0.0052	0.0328	0.0082
	Average dispersion in comparison with the median		0.010	Average dispersion in comparison with the median		0.011

The total data dispersion could be estimated as the difference between the quartiles Q1 and Q2 in their approach to zero. Regarding the dispersion range between the average in comparison with C2C® and Dynamo®, very similar data were obtained, and the average dispersion reached 90.01% (see Table 16). If both procedures were similarly aligned, very similar data would be obtained by maintaining the dispersion proportionality.

10.- Conclusions

The Architecture, Engineering and Construction industry in relation to new layout projects is strongly supporting the use of BIM digital platforms. In the rehabilitation and preservation sector of heritage buildings, advances have been made; however, it should be more developed. So much work related to the logistics and the use of operators is required to model heritage architecture, but the advance is unstoppable. All data provided by this paper, together with the benefits provided by BIM in relation to the activity exploitation, the recording of historical documentation, the quality maintenance and control, and the built modelling, among others [88], show the importance of the implementation taking place in the new paradigm, i.e., in HBIM. The geometric construction containing metadata should be considered, as well as the potential of many applications that can be used in 3D digital

reconstructions. By creating digital twins, this research work analyses the structural deformations in a portico belonging to the courtyard of a hotel from the 18th century. TLS, recommended for large buildings, was used as a technique to acquire accurate data. Moreover, the point cloud was used as a referential auxiliary to build the model in the BIM platform with the Revit software. To assess the quality of the model built and to analyse the structural deviations between the parametric model and the actual geometry, Dynamo© was used. To validate the experimentation, structural deviations were measured with both the parametric model (.stl) and the point cloud in the .e57 format with CloudCompare, a software for data treatment. Based on this dataset, the deviation of the results obtained with Dynamo© and C2C© in the quartiles Q1 and Q3 ranged between 0.5 and 1.7 cm in the most unfavourable case (in the column C1). Compared with the length of the elements, the dispersion could be acceptable, so the techniques mentioned could be used to review the visual recordings and to analyse structural deviations when building parametric objects.

These analysis records could take place in various periods, and the displacement analysis could be seen through an action protocol. Movements recorded deviations in the walls between 2 and 5 cm, which can be considered usual in old buildings because of their characteristics and their historical identity. In addition, the comparison between the model of the point cloud and the parametric model allowed the quality of the model built to be known; effectiveness should also be improved, and the ornamental elements not detected today by the algorithm should be listed. Dynamo© is a visual programming application used to solve many tasks, including the analysis and the creation of routines related to the geometric layout. Thus, data acquisition could be transferred to programs such as Excel© to be treated or parametrically designed, becoming them versatile for BIM operators.

Assessing the dispersions among homologous plans in the same platform is among the advantages of this algorithm, and in other studies the linear analysis was assessed through an independent software. A digital twin reproduces the behaviour of an actual system as response to external physical data [32]. Thus, this algorithm could be a useful tool for both programmers and engineers in relation to structures modelled with BIM and architects who conduct structural analysis campaigns in old buildings. This case study shows that the proposed methodology is greater effective to analyse a structural model. It is both an analysis model as it contains geometric information about the position, size and space to know the mechanical properties, and a detail model where the geometric forms of the structural elements are included [89]. A future research line will be focused on using the SfM technique in the analysis, behaviour, and diagnosis of humidities, as well as in the experimentation related to the distortion, axils and bending of architectural elements. Given the complex scope of study that CH involves, future studies are expected to focus on more complex architectural structures and elements to stress the value of the research. Thus, the new BIM paradigm would be included in an interdisciplinary programming within the area of architectural structures.

Abbreviations

The following abbreviations are used in this manuscript:

TLS	Terrestrial Laser Scanning
SfM	Structure-from-Motion
MDCSs	Massive Data Capture Systems

BIM	Building Information Modelling
HBIM	Historic Building Information Modelling
GCP	Ground Control Points
DBAT	Damped Bundle Adjustment Toolbox
RPAS	Remotely Piloted Aircraft Systems
DSLR	Digital Single Lens Reflex
HDR	High Dynamic Range
RMS	Root-Mean-Square
RMSE	Root-Mean-Square-Error
MVS	Multi-view Stereo
EXIF	Exchangeable image file format

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