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Methodology for Data Integration in 3D-HBIM Digital Models. Case Study: the Holy Chalice Chapel of Valencia Cathedral

The article presents a methodology for integrating data into 3D Heritage Building Information Modeling (3D-HBIM) digital models, specifically focusing on the Chapel of the Holy Chalice case study in the Metropolitan Cathedral of Valencia. This approach is oriented towards efficiently managing and visualising crucial information for conserving architectural heritage. The methodology begins with data acquisition through terrestrial laser scanning (TLS), an advanced technique that enables the acquisition of an accurate and detailed point cloud of the architectural environment.

Following data acquisition, a meticulous process of segmentation and processing is undertaken. This phase involves the use of various machine learning algorithms, including Random Sample Consensus (RANSAC) and K-Means, for data classification. These algorithms play a crucial role in identifying and classifying points based on their geometry and chromatic characteristics. A key feature of the approach is the use of colorimetry-based classification, which detects significant changes in the RGB values of the points, thereby aiding in the identification of patterns and potential deterioration in construction materials.

The processed data are seamlessly integrated into BIM environments, enabling the incorporation of detailed alphanumeric data and the comprehensive visualisation and analysis of three-dimensional models. This integration is pivotal for the accurate representation and analysis of heritage architecture, providing a robust foundation for decision-making regarding its conservation and maintenance.

The article examines the benefits of the proposed methodology, highlighting how the combination of advanced data acquisition techniques and digital processing can significantly enhance the representation and analysis of historical architectural structures.

Keywords:
scan-to-BIM; HBIM; Digital twins; Architectural Heritage; Valencia Cathedral

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INTRODUCTION

In recent years, the evolution of digital technologies focused on the preventive maintenance of architectural heritage has advanced significantly. This process is closely linked to the development of new digital technologies. Specifically, Terrestrial Laser Scanning (TLS) sensors' evolution and rapid data acquisition capabilities have been crucial. Obtaining and analysing this data is vital for detailed building analysis and early detection of pathologies or anomalies.

Moreover, different methodologies, such as Building Information Modeling (BIM) and Geographic Information Systems (GIS), enable visualisation, integration, and analysis of this information within the construction domain. However, the sheer volume of data cannot be directly incorporated into these platforms. Therefore, filtering, segmenting, classifying, and refining information, especially from laser scanning, which often involves millions of data points, becomes necessary.

Recently, significant progress has been made in data integration within Heritage Building Information Modeling (HBIM), establishing itself as a viable option for managing and visualising information generated in architectural heritage documentation and preventive conservation activities. This methodology facilitates the interrelation between different analyses and promotes a deeper understanding of these types of buildings (Angulo-Fornos & Castellano-Román, 2020; Barazzetti et al., 2015; Vitali et al., 2021).

The HBIM approach allows for creating schematic geometric models designed to incorporate multiple levels of information. This capability to combine visual representations with alphanumeric data is crucial for understanding and managing historic buildings, providing experts with the flexibility to comprehensively analyse, document, and plan interventions (Castellano-Román & Pinto-Puerto, 2019; Liu et al., 2022).

The inherent complexity of historic buildings demands meticulous identification and classification of vast amounts of data for their documentation (Brumana et al., 2017). Advanced technologies such as terrestrial laser scanning and photogrammetry capture data precisely (Verdiani, 2019). These techniques, applied to historically significant buildings, yield a wealth of information compared to new construction. However, managing and subsequently classifying this broad range of data requires filtering to streamline diagnostic stages and, ultimately, intervention efforts. Several studies have addressed the segmentation and classification of point clouds (Dong et al., 2018; Sharafutdinov et al., 2023) with varied and significant results. Vo et al. (2015) utilise plane detection in three-dimensional space; Yun-Ting-Su et al. (2016) propose the "Split and Merge" method; Li et al. (2017) suggest using Random Sample Consensus (RANSAC) to decompose point clouds into smaller cells. The Scan-to-BIM process has also achieved workflow for segmenting and generating a BIM model from classified points (Banfi, 2017; Previtali & Banfi, 2018).

Currently, there is a search for a simple and efficient process to combine point clouds obtained from surveys and their interoperability in BIM and GIS platforms. Managing the vast amount of information generated in the study of historic buildings remains a significant challenge. In this context, we propose simplifying point clouds for incorporation into BIM. This work aligns with the objectives of a research project funded by the Ministry of Science and Innovation of the Government of Spain (PID2020-119088RB-I00).

OBJECTIVE

This research aims to address the challenge of efficiently generating a digital twin, a virtual representation of a physical object or system, in this case, historical buildings with complex geometries and characteristics. This digital twin seeks to be a precise virtual replica of the actual physical structure, retaining the geographical coordinates of its elements and facilitating the integration of a wide range of geometric and alphanumeric data based on spatial location.

The process involves working with points obtained from laser scanning or photogrammetry of historic structures. This includes converting the resulting point clouds into geometric models capable of incorporating detailed information about the building's geometry and physical characteristics within a BIM environment. Additionally, the potential integration of alphanumeric data concerning the materials used, the conservation status of structural elements, and any interventions over time is considered. Efficient data handling necessitates filtering the information through segmentation and classification techniques to achieve a high-quality product in minimal time.

The resulting digital twin will enable a three-dimensional visualisation of the building, allowing for the breakdown and analysis of each layer of information individually. Furthermore, there will be an exploration into incorporating the time variable, facilitating observation and verification of changes in the building throughout its history. Thus, the digital twin will not only be a static tool but also a dynamic one, capable of reflecting the temporal evolution of the structure and providing a deeper understanding of its historical and architectural context.

CASE STUDY: THE CHAPEL OF THE HOLY CHALICE

Following the Christian conquest of Valencia in 1238, the principal mosque was consecrated as a church by Bishop Fray Andrés de Albalat (García Edo, 1988). Construction of the new building began in 1262, influenced by the austere Romanesque architecture, exemplified notably by the so-called Romanesque Door or Palace Door (Beuter, 1551), which can still be admired today. The church has a Latin cross plan; originally consisting of three naves and three sections, an additional section known as the "Obra Nova" was added in the 15th century. At the central section of the transept lies the octagonal dome, followed by the construction of the Chapter Hall, now known as the Chapel of the Holy Chalice, along with the bell tower of the Miguelete. This historical transformation from a mosque to a church and the subsequent additions make the Chapel of the Holy

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Chalice a significant part of Valencia's history. Over time, several expansions have taken place, such as the current main entrance, "Porta dels Ferros," the side chapels, the canons' residence, the archive, and the museum, resulting in the current configuration of the building. Due to the various interventions throughout its history, the structure has evolved with layers of architecture from different historical periods. Given its continuous addition of adjacent spaces to the side naves, this complexity makes it challenging to understand as a unified whole. The Chapel of the Holy Chalice, originally separate from the main temple, stands out as an intriguing subject for study due to its historical and aesthetic value and size, which is suitable for exploring the process discussed in this article.
The Chapter Hall or Chapel of the Holy Chalice, a masterpiece of late Gothic style, was constructed between 1356 and 1369 by the master builder Andrés Juliá. Initially distinct from the original building, it was originally intended as the Chapter Hall (Sanchis, 1933). This space, built entirely with ashlar stone, is a nearly cubic space (13 m per side x 16 m in height) that features two distinctive elements: the starry vault that covers it, octagonal in shape, and small triangular vaults in the corners. The exceptional alabaster altarpiece (1415-1424) adorning the front wall, initially designed for the choir facade and relocated to its current position in the 18th century, adds to the unique charm of this space (Fig. 1).
The Chapel was constructed to house the burial of the Canons (Orellana, 1924) and to provide space for theology classes, which is why it features two rows of stone benches along its perimeter and a pulpit for the Master. The master stonemason Pere Compte, known for his work on the Lonja, also participated in its construction. In 1916, this part of the cathedral complex was opened for the worship of the Holy Chalice, and since then, it has been visited by thousands of tourists each year for contemplation (Fig. 2-3).

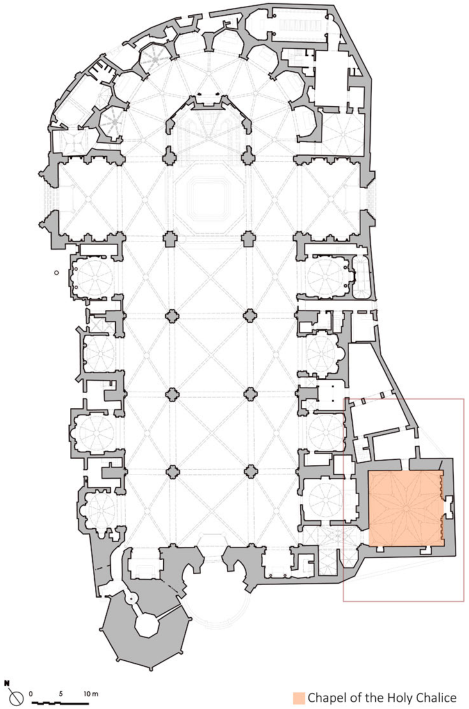

Fig. 1 - Floor plan of Valencia Cathedral.

Fig. 3 - Point cloud of the Holy Chalice Chapel in Valencia Cathedral.

Fig. 2 - Photographs of the Holy Chalice Chapel in Valencia Cathedral.

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METODOLOGY

Within the framework of the R&D&I Project, a comprehensive scan of the entire religious complex of Valencia Cathedral was conducted. For this purpose, two Faro® laser scanners, the Focus Premium S-150 and Focus Premium S-350, with a range of 150 and 350 metres, respectively, were employed. These devices have a 3D accuracy with a margin of error of 2 mm at 10 metres. The survey included 543 stations, with an overall resolution of 1/8 for interiors. The registration of the point clouds was carried out using Faro® Scene 2023.1 software, achieving an average registration error of 1.2 mm and encompassing more than 4 billion points (Fig. 4). The overall point cloud obtained was divided into sectors identified as closed interior areas corresponding to independent spaces: side chapels, central nave, sacristy, ambulatory, archive, offices, museum, etc. This facilitated an initial classification based on the different areas of the Cathedral. Subsequently, elements of interest, such as each enclosure's vaults, walls, and pavements, were identified and selected, thereby segmenting the point cloud according to the construction components.

It aims to conduct a survey for subsequent modelling in BIM to create a digital twin of the building; a methodological strategy was designed, focusing on the efficient processing of the obtained point cloud. The Chapter House, the Chapel of the Holy Chalice, was chosen as a test laboratory. This choice was based on this enclosure's dimensional, formal, architectural, and material characteristics. It is large and covered with a complex ribbed vault. It has various types of arches at its entrances and circular and triangular oculi; its walls are made of stone ashlar, and one of its sides is covered with a large alabaster altarpiece. All this constitutes an appropriate diversity for testing the proposed methodology.

In this enclosure, twelve scans were conducted, covering both the exterior and interior of the Chapel of the Holy Chalice. These original point clouds were processed and segmented to reduce the information volume, maintaining the points' exact location without losing the original sample density. The segmentation and classification of the point cloud were performed through a subsampling process, in which the number of points was reduced without significantly compromising the model's accuracy.

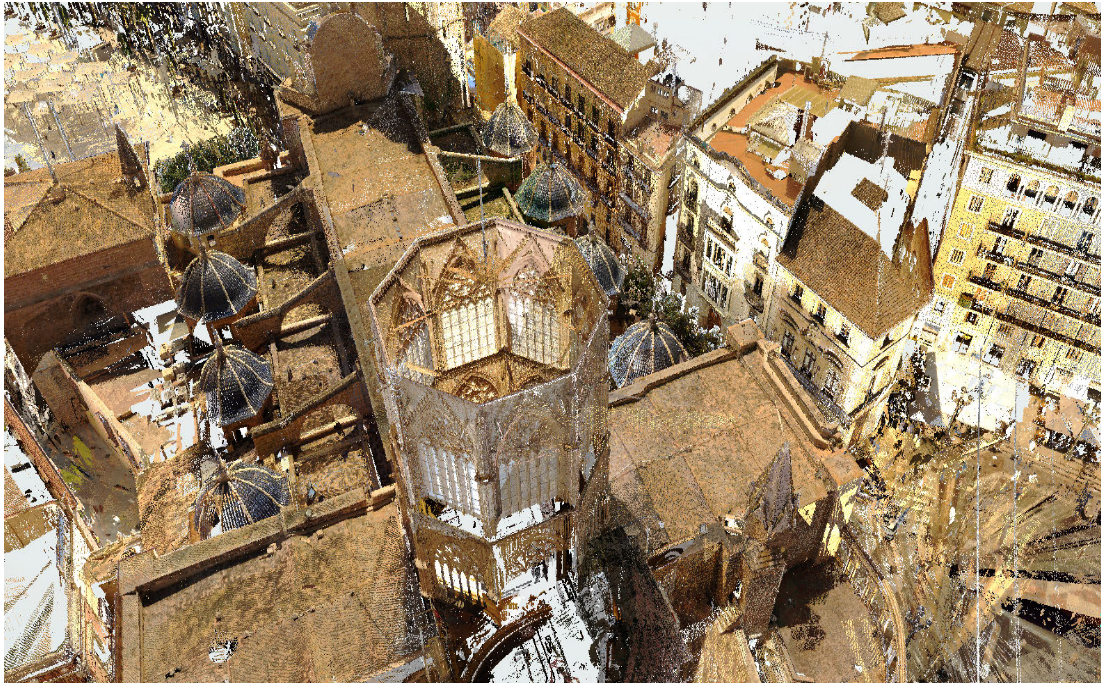

Fig. 4 - Complete point cloud of the Valencia Cathedral

The original sample of the Chapel of the Holy Chalice consisted of 90 million points for a volume of 3548 m³, with an average point spacing of approximately 0.002 m. This sample was simplified through the subsampling process using the open-source software CloudCompare, adopting a point spacing of 0.05 m, which generated a subsample of 480,000 points, meaning the elimination of 95% of the points. This significantly reduced the number of points to facilitate information processing, reduce redundant data, and maintain adequate point spacing for subsequent analysis. It is crucial to consider the volume of data to be processed, necessitating the reduction of redundant data. From this final sample, the normals were calculated, which helps determine the orientation or direction of each point concerning its surrounding environment. This task facilitates various analyses on the same.

The planes that form the pavement of the point cloud were separated. This was achieved by analysing the inclination angle of the surfaces concerning a horizontal plane of the point cloud, using the Dip/Dip direction. This evaluation effectively distinguished the horizontal plane of the pavement. Thus, the points belonging to the pavement were accurately classified (Fig. 5).

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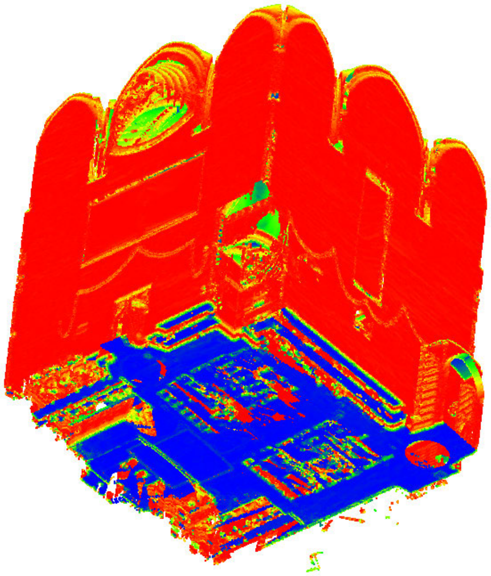

Fig. 5 - Segmentation of the pavement in the point cloud of the Chapel of the Holy Chalice.

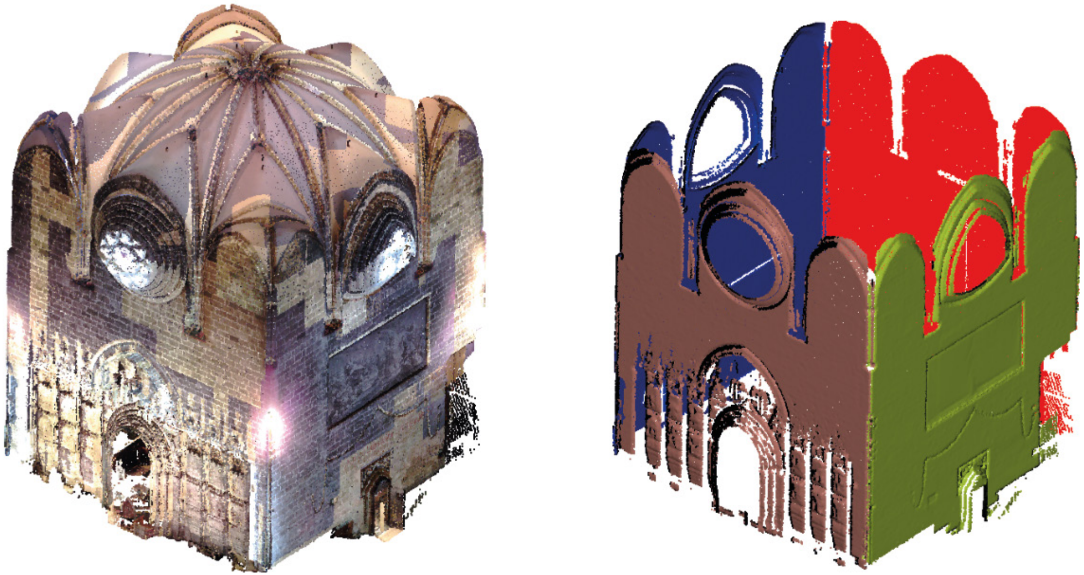

Fig. 6 - Point cloud of the interior envelope of the Chapel of the Holy Chalice and segmentation using RANSAC.

To differentiate between the points corresponding to the walls and vaults in the point cloud, the Random Sample Consensus (RANSAC) algorithm was implemented. This algorithm automatically detected various geometric shapes, enabling the classification and segmentation of points based on plane discretisation. Specifically, RANSAC identified shapes formed by spherical and cylindrical surfaces based on arches, which is particularly useful for analysing the vaults. To optimise processing, the data analysis was restricted to a specific range of radii, between 0.5 m and 15 m (Schnabel et al., 2007) (Fig. 6).
Upon completing the data processing with RANSAC, new entities were generated that were equivalent to a point cloud segmentation and classified based on the detected shapes. This process allowed for a semantic classification of parts based on geometries, involving identifying and labelling different components within a three-dimensional environment. Using the analysis provided by the RANSAC algorithm, it was possible to distinguish between planes and cylindrical and spherical surfaces within the point cloud, allowing for the identification of specific architectural features such as walls, vaults, and arches (Fig. 7). Additionally, this automated process enabled the precise determination of the radii of the arches and vaults. The classification labels provided a detailed understanding of the various interior surfaces within the building, facilitating further analysis and processing in modelling applications (Figs. 8-9).
A second classification was based on the RGB data of the point cloud, starting with the colourimetric

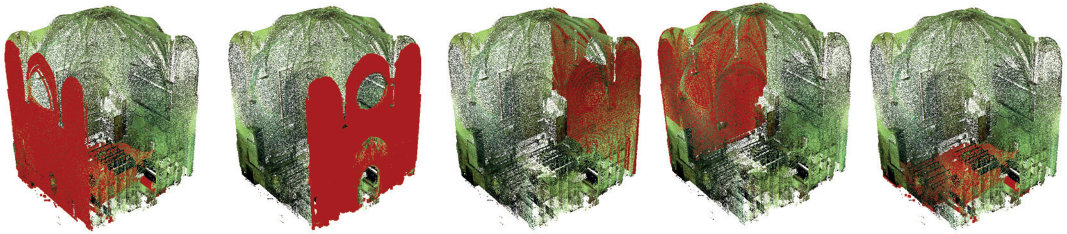

Fig. 7 - Classification of the envelope of the Holy Chalice Chapel using the RANSAC algorithm.

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classification of the points obtained through laser scanning. This classification allows decoding the information of the point cloud, providing local coordinates (XYZ) and RGB values representing the colour information.

Our main objective was to identify areas with significant chromatic changes, which could indicate the presence of some surface chromatic anomaly, and also the possibility of generating segmentation based on chromaticism (CloudCompare, 2024). The first step in this process involved simplifying the RGB values of the sample points to facilitate their handling and subsequent analysis (Fig.11). This simplification was achieved by applying processing tools available in the software, which allowed us to reduce the complexity of the data without compromising the number of points.

Subsequently, the points were classified based on their synthesised RGB values. This stage was crucial for identifying specific patterns and features on the wall surface. To achieve effective classification, ranges of RGB values representing the different shades on the wall surface were established. These ranges were carefully selected according to the expected characteristics and possible chromatic changes.

Fig. 9 - Classification of the surfaces of the vault of the Chapel of the Holy Grail using the RANSAC algorithm.

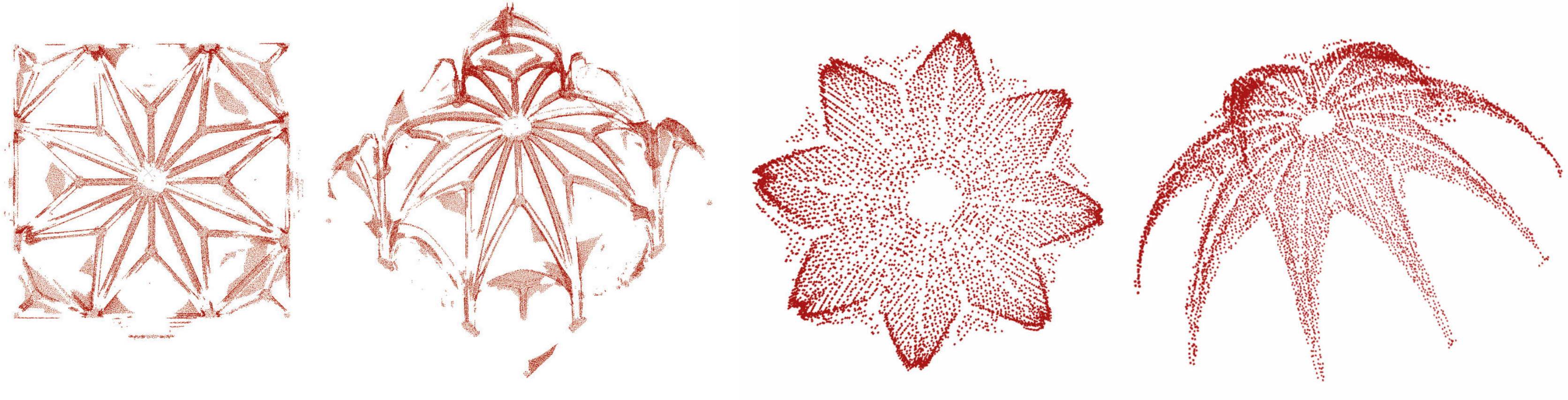

Fig. 10 - Detection of vault nerves in the Chapel of the Holy Chalice using the RANSAC algorithm.

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Once the classification criteria were applied, a visual representation of the areas of interest in the sample was obtained, highlighting regions with significant changes in RGB values. This visual representation was then analyzed by quantifying the number of colours using the K-Means Clustering algorithm. The algorithm played a crucial role in simplifying the diversity of colors present in the sample, thus facilitating the identification and elimination of possible artifacts or visual noise.

The various point clouds resulting from the classification were subsequently integrated into a BIM environment through an automated workflow. A specific routine was developed using tools such as Autodesk Revit and Dynamo to achieve this. The georeferenced information (X, Y, Z) and the RGB values from the camera associated with each point of the cloud were utilised.

Furthermore, all previously generated analysis layers were incorporated into a single BIM model, simplifying the extraction of information about the point clouds and allowing the application of various visualization filters in BIM (Fig. 12). This process greatly simplified the discretization of surfaces and volumes through more detailed BIM geometries, enabling the integration of data into a three-dimensional model exportable to the standard Industry Foundation Classes (IFC) format.

Additionally, this model can be integrated into GIS (Geographic Information Systems) environments using its geographic coordinates.

RESULTS

This methodology provides a systematic and efficient workflow for processing and analysing point clouds to create a detailed digital model of a historic building while maintaining the accuracy and integrity of the original data. It offers significant advances by enabling the export of point cloud classifications and segmentations to BIM models. This is achieved by exporting the point cloud as an IFC file, which can be visualised and imported as a BIM model, preserving all its metadata.

The high resolution obtained allows for various data to be included at each point, such as types of materials, pathological conditions, and real-time information generated by sensors, among other possibilities. Additionally, it is possible to identify each surface by incorporating parameters and exporting this information to IFC format. This process optimises the integration of geometric and alphanumeric data in an HBIM environment. It establishes an automated process to manage a large data volume and allows for its visualisation through digital models for deeper analysis.

Colour range-based analysis, a key feature of this methodology, allows for the classification of points to assign a material parameter in a BIM model. This means that specific points belong to a particular type of wall and are made of a specific material. This not only enables us to calculate the surface area of each material using voxel measurements in which the BIM model is generated (Fig. 13) but also opens up possibilities for deeper analysis.

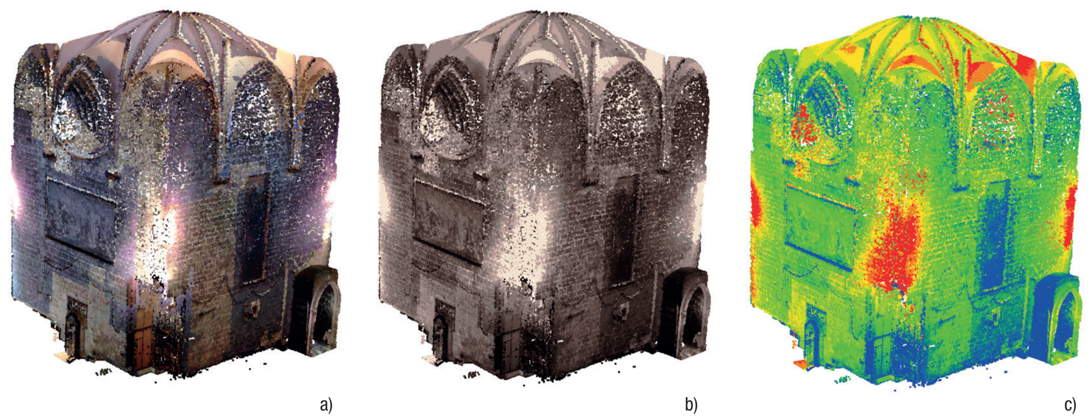
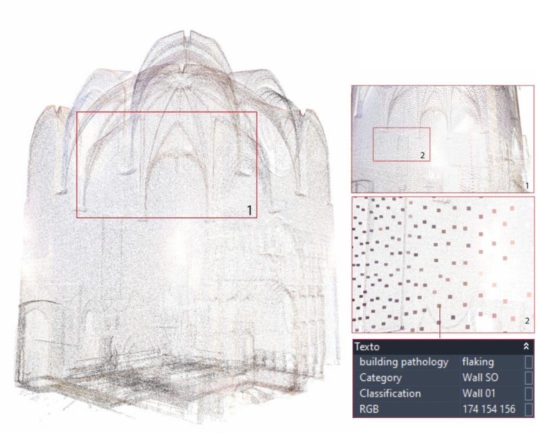


Fig. 11 - a) Original cloud, b) Simplification of RGB values, c) Classification using the K-Means algorithm.



Texto	
building pathology	flaking
Category	Wall SO
Classification	Wall 01
RGB	174 154 156

Fig. 12 - Visualization of the point cloud as a family within a IFC-BIM model.

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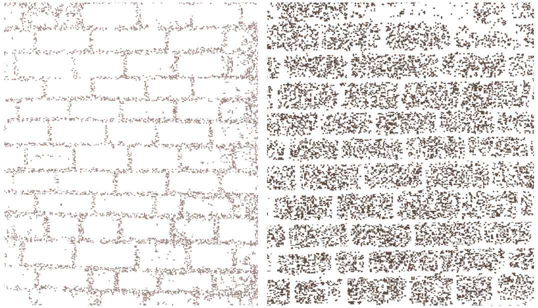

Fig. 13 - Detection of the points belonging to the stone ashlars based on colour ranges.

CONCLUSION

This methodology provides a systematic and efficient workflow for integrating data into 3D Digital Heritage Building Information Models (3D-HBIM). This approach focused on managing and visualising information for the conservation of architectural heritage, using data acquisition through terrestrial laser scanning followed by the processing and segmentation of the resulting point cloud. Classification algorithms such as RANSAC and K-Means allowed us to identify and classify points based on their geometry and chromatic characteristics (Fig. 14). Additionally, colourimetry classification to detect significant changes in RGB values facilitates the identification of patterns.

By combining point clouds with the HBIM methodology, we have unlocked significant potential for representing and analyzing architectural heritage. The ability to visualize the current state of a heritage building through point clouds in a single tool greatly enhances the understanding of the building and contributes to decision-making regarding its conservation and maintenance. The processed data was seamlessly integrated into BIM environments, allowing the incorporation of alphanumeric data, as well as the visualization and analysis of detailed 3D models. The benefits of the proposed methodology for representing and analyzing architectural heritage were thoroughly examined, highlighting its potential to facilitate decision-making in its conservation and maintenance.

By simplifying point cloud data through segmentation and classification, we developed an optimised workflow for Scan-to-BIM processes, improving efficiency in handling the large volumes of information generated in the study of historic buildings. Our methodology allows for the creation of accurate digital replicas of complex structures and facilitates their dynamic exploration over time.

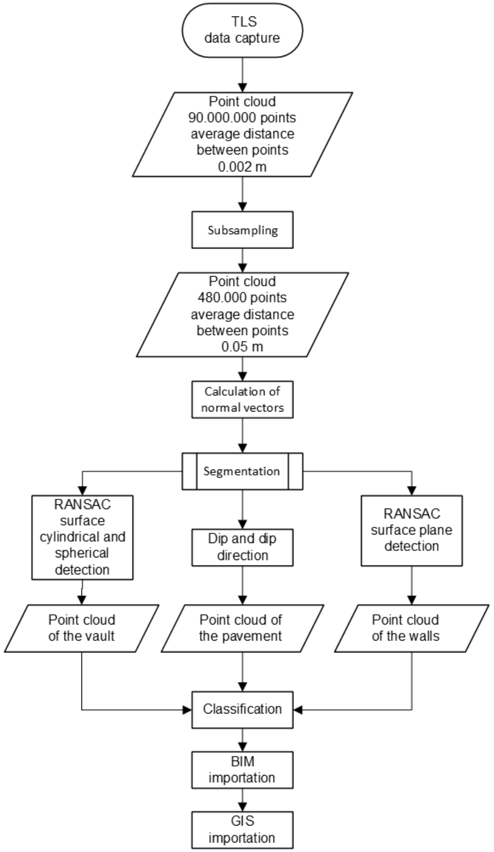

Fig. 14 - Schematic diagram summarizing the workflow

While our methodology offers significant advantages, it is not without its limitations. For instance, we observed that RGB values respond to the exposure measurement made by the scanner's camera, resulting in divergence in the homogeneity of the data obtained. Therefore, it is necessary to use this information as a guide rather than an absolute. Another limitation found is related to the volume of information generated, which requires adopting simplification criteria at each phase of the process. These limitations are important to consider when applying our methodology.

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