POINT CLOUD SEGMENTATION IN HERITAGE PRESERVATION. ADVANCED DIGITAL PROCESS FOR HISTORICAL HOUSES

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ABSTRACT:

This paper discusses the use of point cloud segmentation, both automatic and semi-automatic, in heritage conservation processes, with the aim of consciously integrating traditional and innovative methods. Thus, the research explores the potential of open-source software tools for semi-automatic point-cloud segmentation in enriching heritage knowledge and contributing to the inspection of its state of conservation. This ensures a 3D geometric view of reality and enables the identification of criticalities that may not be visible to the naked eye through colorimetric attributes. The study was conducted on Villa Leonardi, a historical house located in the city of Treia in the Marche Region (Italy) as a pilot test. The investigation focused on the east and south elevations of the building, which were suitable for two distinct trials: a semi-automatic procedure for analyzing the quality of mortar joints in an exposed masonry, and a semi-automatic procedure for mapping alterations and decay in a plastered masonry. To validate the results, manual and semi-automatic maps were compared using both qualitative and quantitative assessments. Qualitative assessment involved overlay and visual analysis, while quantitative assessment involved transforming the segmented point cloud into a mesh and calculating the resulting surface area. The critical interpretation of the two trials revealed both advantages and disadvantages; overall, experimentation highlighted the added value that advanced digital process can bring to the issue of heritage preservation.

1. INTRODUCTION

Since the 1990s, and increasingly in recent decades, the development of Information and Communication Technologies (ICTs) has had a significant impact on the field of cultural heritage and digitalization has become a potential catalyst for heritage preservation (De Vos P.J. et al., 2023; Oomen J. and Bočytė R., 2019). It is important to note that the most challenging use of digital technologies does not consist in computerising traditional conservation processes, but rather in renewing and integrating them with new ones to achieve higher objectives in terms of quality, efficiency and sustainability (Dimitrova et al., 2019; SIRA, 2023). This aligns with a predictive and process-oriented vision, as well as a multidisciplinary approach to the built environment as a whole.

The discipline of restoration, along with conservation experts, has embraced the challenges presented by the digital realm, resulting in a variety of theoretical and applied studies. This has also fostered new synergies and alliances among professionals and stakeholders, adhering to the concept that innovation thrives when diverse research stimulates one another (Daniotti et al., 2020; European Commission, 2012).

As a matter of fact, any activity related to historical architecture requires a wide range of knowledge and skills, starting with the recognition of heritage values during the earliest stages of the asset investigation. Immediately afterward, geometric surveying should be conducted as a revealing tool primarily for the building morpho-metric properties. The accuracy and comprehensiveness achieved by new acquisition methods have undoubtedly been a key driver for the digital transition in heritage preservation. Advanced digital technologies have provided valuable insights into the critical evolution from geometric surveying to historical, physical-material, structural, stratigraphic and degradation knowledge of the architectural heritage. Such a process has also maximised the use of integrated digital survey data to successfully contribute to restoration projects and, above all, to prevention, risk preparedness and mitigation, maintenance and management in a green and sustainable perspective (Muench et al., 2022).

In this sense, digital data management is crucial for the success and quality of heritage conservation strategies. Nevertheless, this is a very complex issue as it requires an integrated representation of heterogeneous information in order to design appropriate programmes. In the process of integrating traditional and innovative methods and tools, Historical Building Information Modeling (HBIM) has proven to be powerful and challenging for managing heritage complexity. In (Diara and Rinaudo, 2019) a modelling process using NURBS surfaces and the use of open-source software is tested and found to be effective. Starting from 3D data obtained through a well-established process of reality capture, including image-based and range-based techniques, an important driver for knowledge-building is to enhance semantic information. As demonstrated by (Allegra et al., 2020), the Scan-to-BIM methodology has turned out to be a very efficient tool to include the multidisciplinary information concerning the monument in a single digital environment, to draw up documentation that can be updated and implemented over time and to ensure optimal management of the building. In this study, the different modelling approach between parametric and not-parametric architectural elements was tested. In other studies, to create parametric libraries of architectural elements from point clouds, the approach is modelling by subjective interpretation or manual segmentation (Quattrini et al., 2015). In the same way, some researches show the manual redrawing of maps and degradation information within the BIM environment (Brumana et al., 2017; Di Stefano et al., 2020).

In HBIM platforms, comprehensive semantic annotations for parametric components are effortlessly achieved. Moreover, by including suitable parametric adaptive components, it becomes feasible to expand this capability to localized elements. This functionality is crucial for information systems dedicated to the preservation and restoration of cultural heritage, allowing for the

annotation of localized areas affected by damage or degradation (Croce et al., 2020). Automatic or semi-automatic annotation regarding the heritage state of conservation, is an attainable target in the case of reality-based models.
Despite this, segmentation continues to be a persistent challenge, particularly when dealing with ancient, intricate, and geometrically complex objects. These objects often exhibit anomalies and gaps attributed to environmental factors like earthquakes, pollution, wind, and rain, as well as human-related influences. Nowadays, segmentation algorithms are widely used in the literature and act on two types of raw data properties: 3D geometric features (coordinates, normal vectors, derivatives) and 2D colorimetric attributes (RGB colour values) (Musicco et al., 2021). Used for the recognition of architectural elements with good results (Hamid-Lakzaeian, 2020), they are also tested for the detection of surface alteration or decay. In (Gonizzi Barsanti et al., 2017), authors test several methodologies and algorithms available to segment a 3D point cloud or a mesh for cultural heritage structural analysis. While other work shows how to exploit a semi-automatic segmentation method to improve material characterization, only based on the point cloud (Mugnai et al., 2021).
In this field, Machine Learning (ML) algorithms are increasingly being applied to automatic classification processes. Nevertheless, applications for degradation mapping are often customized for specific cases, such as heritage sites of considerable size, or require extensive image datasets to effectively train the algorithms, particularly when using deep learning processes. Some authors present a framework for detecting structural damage on the surfaces of intricate heritage structures by leveraging both visual 2D and 3D data. Using deep learning and computer vision, they detect damages within images of heritage sites and then proceed to precisely locate the identified damage on the corresponding 3D models (Grilli et al., 2018; Pathak et al., 2021). (Adamopoulos et al., 2021) design a workflow for two-dimensional mapping based on low-cost visible and near infrared-spectrum imaging and ML tools; then, they evaluate the approach for annotating identified surface patterns.
On the other hand, some works test semi-automatic procedures for data mining relating to the state of conservation of the architectural heritage, thanks to the processing of point clouds. These methods aim to offer quantitative data, which is sometimes difficult to measure on site. Indeed, (Valero et al., 2020) outline an innovative tool for the semi-automatic segmentation of 3D point clouds of rubble-constructed stone walls into individual masonry units and mortar regions. In this way, other studies prove the potential to extrapolate useful information in diagnostics using the algorithms already implemented in open-source software (Nespeca and De Luca, 2016).
As demonstrated by this brief overview, segmentation, both automatic or semi-automatic, is a still open topic of research in the integration and updating of traditional conservation methods and tools; therefore, it appears to provide a useful and necessary technological support for the issue of heritage preservation.
[CM; RN]

2. RESEARCH AIM

The paper explores the integration of traditional methods with advanced digital technologies to support processes of critical interpretation and preservation of cultural heritage. Specifically, it examines and ties to overcome the limitations of some well-established procedures for analysing the state of conservation (alteration, decay and cracks) of historic architectures. These procedures are typically based on visual on-site inspections, followed by laboratory instrumental analyses of material samples. Similarly, the study highlights that the canonical 2D representation of degradation maps may not always be sufficient to describe all observable phenomena, some of which involve 3D development, such as cracks, missing elements, or erosion of mortar joints.
The aim of the research is, therefore, to investigate the potential of open-source software tools for semi-automatic point-cloud segmentation to enrich heritage knowledge and contribute to the inspection of its state of conservation. This ensures a 3D geometric view of reality and enables the identification of criticalities that may not be visible to the naked eye through colorimetric attributes.
This study adopts a strictly operational approach, discussing two trials that both begin with the processing of point cloud data obtained from the integrated digital survey. The applied solutions are closely linked to the physical and material characteristics of the architecture in the case study, including exposed or plastered masonry.
The first trial is directed at the semi-automatic generation of a material consistency map of a 1m x 1m sample of exposed masonry. This map enables the extraction of quantitative data related to associated elements, such as bricks and stones, with particular attention to mortar joints, which are the most vulnerable to the action of atmospheric agents. This application has also potential implications in the calculation of the Masonry Quality Index of historic buildings, which is widely used in designing heritage conservation and reinforcement works (Borri and De Maria, 2015).
The second trial focuses on the semi-automatic creation of 3D thematic maps to describe the alteration and decay phenomena of external plastered surfaces in the case study. These maps can be seamlessly integrated as semantic information layers in HBIM.
Both experimental trials should be considered as complementary to traditional procedures for heritage preservation, rather than alternatives. They are rooted in the fundamental principle of scientific evaluation by those involved in the conservation process, without losing sight of the challenging perspective of research in the field of digital technologies through automatic and/or semi-automatic approaches. [CM]

3. CASE STUDY AND METHODOLOGY

3.1 Villa Leonardi, Treia (MC), Italy

The research was conducted at Villa Leonardi, a historical house located in the municipality of Treia, in the province of Macerata, within the Marche region of Italy. The selection of the case study was motivated by a dual rationale: firstly, due to the diversity of building constituent materials and the prevalence of various alteration and decay phenomena in terms of both extent and risk; secondly, because it exemplifies the typology of the 'historical private house', which was widespread in the landscape of this region between the 19th and 20th centuries. In this regard, the replicability of the methodology could ensure comparative analyses for a deeper knowledge of this heritage system.
The critical understanding of Villa Leonardi began with bibliographic and archival research, followed by a focus into materials and the state of conservation of the asset.
The villa was built at the end of the 19th century on the remains of a pre-existing farmhouse, and for about a century it served as an aristocratic residence and later as the main building of the Leonardi family's agricultural farm (Bonifazi, 1997). Currently, it has been unused for several years. The building is set within a private garden of 7,000 square meters, which also includes two agricultural outbuildings and a tree-lined boulevard. In 2006, the

property was declared of historical and artistic interest in compliance with the Italian Legislative Decree 42/2004.
The villa consists of a three-level compact volume, flanked by two smaller buildings, formerly used as a family chapel and a warehouse. In terms of construction, the building is characterized by load-bearing masonry, while the roof is made of wooden timber, like a significant portion of the floors.
The most noticeable feature of this asset is the material and geometrical contrast between the front and rear façades. The entrance facade is made of exposed brick, with the central part of the volume slightly protruding, featuring a three-arched loggia on the ground floor and pilasters framing the windows on the first floor. The flanking volumes have mixed exposed masonry, using both brick and sandstone blocks. In contrast, the rear facade and partially the lateral ones have masonries covered with white concrete plaster. This is the result of transformation works that do not always correspond to the historical value of the house, modifying its geometries and surfaces.
The two facades also exhibit different levels of conservation. The entrance facade displays only deteriorated mortar joints, while the rear facade is affected by localized cracks and deformations, detachments especially at the top, washing out, rising damp, hygroscopic behaviour of concrete plasters due to the presence of salts, as well as the presence of biological colonization mostly concentrated at the lower parts of the building. In general, alterations and decay are caused by water infiltrations, lack of use and regular maintenance (Fig.1).
At the outset of the research, the representation of the heritage state of conservation was made using 2D thematic maps, which are typical graphical layouts for restoration projects. The maps were created in compliance with national and international lexicons for the preservation of cultural heritage, including Italian Standard 1/88 and its update UNI 11182:2006, as well as the ICOMOS-ISCS illustrated glossary. Each phenomenon was localised and identified with a coloured region, as described in the key (Fig.2).
This 2D representation was used to validate the trials mentioned above. Both aimed to demonstrate the use of 3D survey data in semi-automating the process of detecting heritage state of conservation. This was achieved through the segmentation of point clouds and the use of both geometry-based and colour-based segmentation algorithms. The selection of algorithms was based on the surface features where degradation phenomena were identified. [CM; LP].

Figure 1 Villa Leonardi, Treia (MC), Italy. General views of the exterior and details of some alteration/decay phenomena.

Figure 2 The south façade of Villa Leonardi. Orthoimage by point cloud (left) and map of the state of conservation (right).

Figure 3 Workflow of the proposed methodology.

3.2 Point cloud segmentation in heritage preservation workflow

This research follows a well-established integrated architectural survey procedure, focusing on two aspects: the data mining in addition to captured data from acquisition phase and the semi-automatic segmentation of the 3D point cloud. Data was processed using an open-source software Cloud Compare and available plug-ins. Segmentation was tested along two approaches, colour-based and geometry-based, both aimed at identifying the state of conservation of Villa Leonardi (alteration/decay), classified according to their main connotation (2D colorimetric attributes or 3D geometric features).
The investigation focused on the east and south elevations of the building, which were particularly suitable for two trials:

- a semi-automatic procedure for analysing the quality of mortar joints in an exposed masonry;
- a semi-automatic procedure for analysing alteration/decay phenomena in a plastered masonry.

To validate the results, manual and semi-automatic maps were compared through both qualitative and quantitative assessments.
The pipeline (Fig.3) consists of the following steps:

1. Digital survey campaign carried out by integrating different data capturing techniques;
2. Raw data processing aimed at providing 2D and 3D digital graphic support for the conservation and management process;
3. Data mining of added geometrical information on the 3D point cloud;
4. Colour- and geometry-based 3D point cloud segmentation;
5. Validation with qualitative and quantitative comparisons. [RN]

4. DATA ACQUISITION AND PROCESSING

4.1 Integrated architectural survey

At the same time, the critical understanding and an accurate digital integrated survey were carried out. A combination of Terrestrial Laser Scanning (TLS), high-resolution 360° imaging, and photogrammetry was employed to ensure both geometric and colorimetric accuracy. The entire 3D survey was carefully planned to achieve uniform lighting and minimize harsh shadows. The data collection took place over a single day and involved two operators. Black and white targets were placed on the ground to define the reference system, which was surveyed uusing a GPS HiPER HR with RTK (Real Time Kinematic) method. Subsequently, the TLS Leica Geosystem P40 ScanStation was used to scan both the exterior and interior of Villa Leonardi from ground level. Set to a scan density of 6.3 mm at 10 m, a total amount of 50 scans were required to document the whole building.
Furthermore, at each scan station, 18 images were captured using a Sony α9 digital camera equipped with a CMOS sensor measuring 35.6 x 23.8 mm and approximately 24.2 megapixels. The camera was rotated using a Nodal Ninja 3 panoramic head to maintain a fixed nodal point aligned with the TLS sensor. To ensure color accuracy and exposure consistency for each image set, photographs were taken using an X-Rite ColorChecker Classic for white balance correction and exposure adjustment. Finally, a photogrammetric survey using an Unmanned Aerial Vehicle (UAV) was conducted with a DJI Mavic Mini. The UAV system is equipped with a 6.17 x 4.55 mm CMOS sensor boasting 12 megapixels. A total of 76 images capturing the upper sections of the building were acquired during a flight at an altitude of 30 meters above ground level. At the end of the survey campaign, the software Leica Cyclone Core was employed to colorize each TLS point cloud using the RGB values obtained from stitching the 18 images captured at the corresponding scan station into a 360° panoramic image. Subsequently, all TLS point clouds were aligned to create a unified representation encompassing both interior and exterior spaces visible from ground level. Concurrently, images acquired by the UAV underwent processing in Agisoft Metashape using the SfM-DMVR method, resulting in another RGB-colored point cloud depicting the roof and two terraces on the first floor. The coordinates of the black and white targets were then used to reference both the TLS and SfM-DMVR point clouds to the WGS84 coordinate system, facilitating their merger. The result was a comprehensive point cloud of the entire building, serving as a digital replica and as basis for accurate as-built 3D modeling within the scan-to-BIM process (Angeloni et al., 2023) (Fig.4). [RN]

Figure 4 Point cloud perspective view of the integrated survey.

4.2 Data mining and point cloud segmentation

After the creation of a single model space containing the entire building, the data processing and data mining were performed within the open-source software CloudCompare. A preliminary cleaning of the point cloud was carried out by removing windows, shutters, doors, debris plants and weeds present in the surrounding environment. Then the point cloud was filtered using the Noise and Gaussian Filter and the RGB values of the points were converted to a Scalar Field, in addition to the reflectance value (Intensity), which was already captured by the TLS tool. The following paragraphs detail the data mining and the segmentation phases on the point cloud, according to the already introduced procedures. [AM; RN]

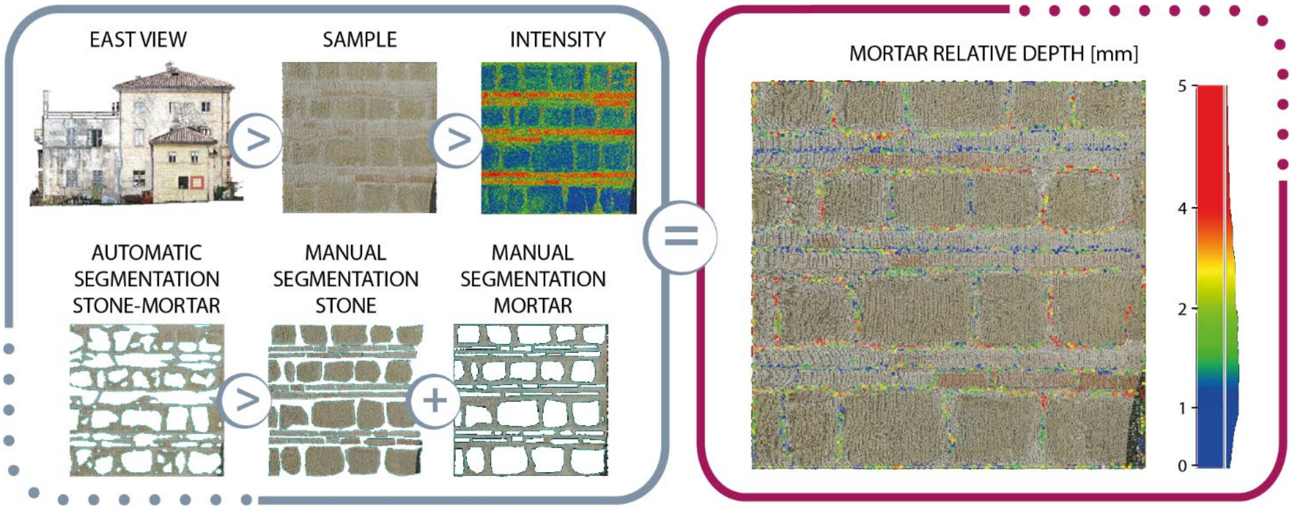

Figure 5 Results of the semi-automatic segmentation: a material consistency map and the mortar joint depth dimensions.

4.2.1 Semi-automatic procedure for masonry quality in mortar joint analysis

The first trial was conducted on the east façade of the Villa, which features exposed masonry with mixed materials such as bricks, sandstone blocks, and mortar. Here, a 1m x 1m study area was isolated. The masonry materials can be easily identified through the Intensity values and an algorithm based on the Continuous Wavelet Transform: sandstone is represented in blue, bricks in red, and mortar joints in green. The process begins by applying an automatic segmentation to the materials and including an estimated input of the width of the sample's joints. This divides the point cloud into sub-cloud, respectively: a cloud for bricks, one for the mortar joints and one for the centre line of the joints that shows their depth and width (Valero et al., 2020b). Although first result is not extremely accurate, it serves as a useful starting point; thus, manual segmentation is necessary. After separating them, the algorithm improves the analysis of the joints and provides their size in millimetres. The output map indicates that the red parts of the joint are the most damaged, while the blue parts are nearly intact.
This process can be a useful aid in critically assessing the condition of exposed masonry. Specifically, the described analysis can contribute to the calculation of the Masonry Quality Index. This methodology is well-established in the literature and provides a numerical index correlated with masonry quality, aligning with the most significant mechanical parameters for masonry. The process of calculation, which is distinct for the three possible directions of stress affecting the masonry, involves assigning a compliance rating for specific parameters that are typical of the rules governing the "art of masonry construction". They include the depth of the mortar joint and its effective contact between the elements. The integration of the discussed semi-automatic procedure into this calculation process can facilitate the interpretation of mortar joint parameter, augmenting a purely visual qualitative assessment (Fig. 5). [AM; RN; CM]

4.2.2 Semi-automatic procedure for alteration/decay analysis in plastered masonry

Focusing on the south facade and based on the heritage critical understanding and integrated survey, the point cloud was processed to apply the second trial.
Alterations and decay affecting the historic building were investigated and categorised according to their main connotation (2D colorimetric attributes or 3D geometric features). Then, a descriptor was assigned to each phenomenon to best represent it (see Table 1).

Alteration/decay	Typology	Descriptor
Discolouration	2D	RGB
Soiling	2D	RGB
Scaling	3D	C2M
Bursting	3D	Intensity
Blistering	3D	Illuminance

Table 1 List of the alteration/decay, classified according to typology and associated with the most appropriate descriptor.

To identify the most significant descriptors, several attempts were made to extract and verify data. To this end, additional geometric information, such as Cloud-To-Mesh distance (C2M) and Illuminance was extracted, in addition to the data collected in the fieldwork (RGB and Intensity) (Fig.6), using two tools:

- *RANSAC Shape Detection* (best fitting plan), for lead and detachments significant (scaling);
- *Portion of Visible Sky* (PCV / Shade Vis) for the identification of bulges of the wall (blistering).

The *RANSAC Shape Detection* (best fitting plan) is used to create the best fitting plane for the entire wall. Once the plane is generated, the distances between the mesh, the plane, and the cloud are calculated to show any accentuated differences compared to the created plane. This provides useful information that may not be visible to the naked eye or that we tend to minimize without accurate measurement.
The *Portion of Visible Sky* (PCV / Shade Vis) is a plug-in used to calculate the light that reaches the point cloud as if it was illuminated by a hemisphere; the calculation only uses normal vectors. By changing the values of the Scalar Field, contrast can be improved to bring out the shadows that the different reliefs produce on the wall and recognize them (Tarini et al., 2003).
Finally, filtering the descriptors, two semi-automatic segmentation approaches were applied, based on colour or geometry, according to the characteristics of the investigated alteration/decay. For the first, the *Colorimetric Segmenter* plug-in was also used. Establishing a range of RGB values, the point cloud was segmented, isolating all points within the chosen range. It is important to note that for both the extraction of new descriptors and the segmentation of the point cloud, the parameters selection is crucial for successful results (Fig. 7). [AM; RN]

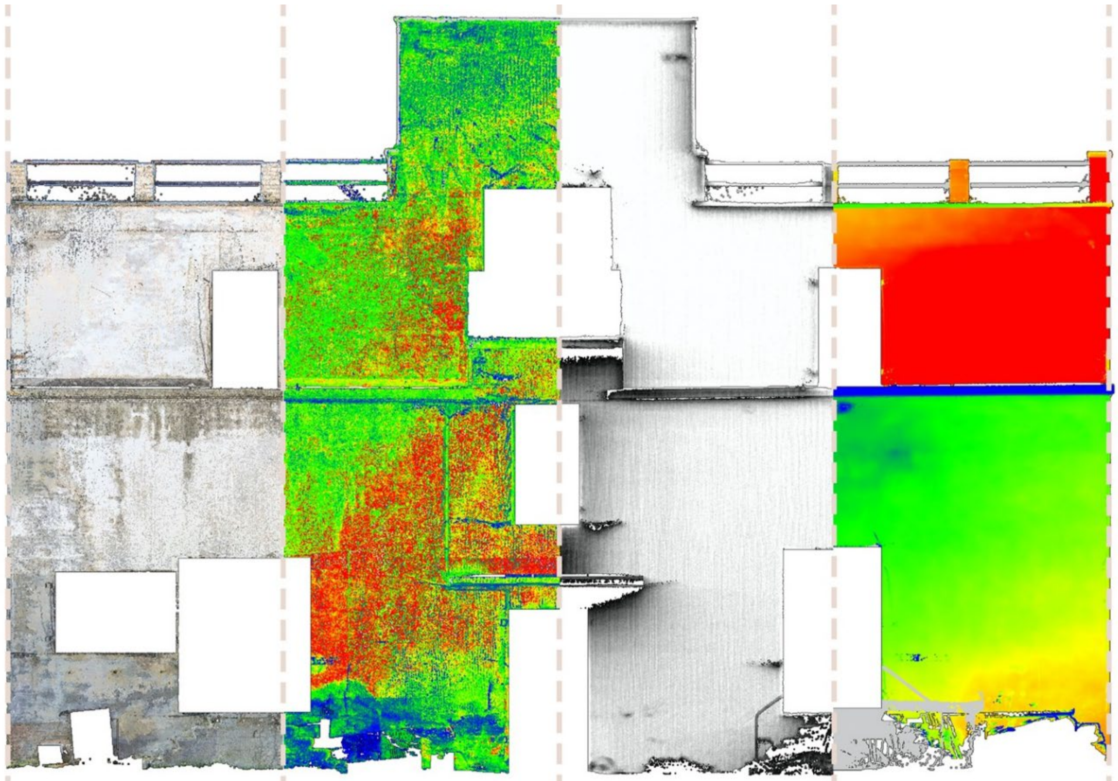

Figure 6 From left to right, the descriptors/tools used for the point cloud segmentation: RGB value (Colorimetric Segmenter), Intensity (Laser Scanner), Illuminance (Portion of Visible Sky), Cloud to Mesh (RANSAC Shape Detection).

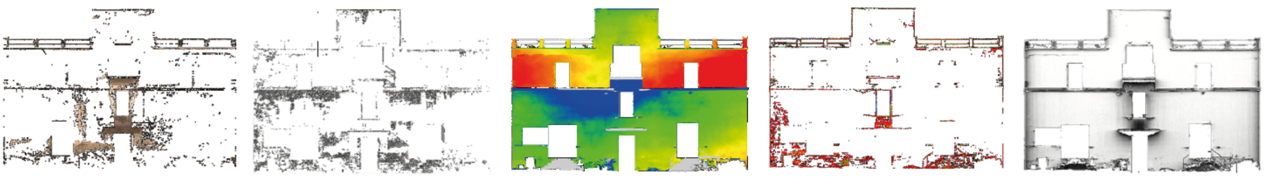

Figure 7 Maps resulting from point cloud semi-automatic segmentation, using the tool associated to the alteration/decay.

4.3 Validation results and discussion

To validate the results, manual and semi-automatic maps were compared through both qualitative and quantitative assessments. In the first case, this was done through overlay and visual analysis, while in the second case, it involved transforming the segmented point cloud into a mesh and calculating the resulting surface area (Fig. 8).
Four different procedures were tested to calculate the area, and the most accurate one was selected and applied to the quantitative assessments of all alteration/decay phenomena identified through the semi-automatic segmentation procedure described above. Specifically, the four algorithms tested are:

- *Mesh 2.5D (Delaunay – Best fitting plan);*
- *Mesh 3D (PoissonRecon);*
- *Automatic Contour (Cross Section);*
- *“Voxel Surface”.*

The first algorithm, called *Mesh 2.5D (Delaunay - Best fitting plan)*, is to create a mesh on a point cloud by projecting the 3D points onto the best fitting plane. The resulting 2D points are then transformed into meshes and the structure is applied to the 3D points. The *PoissonRecon* plug-in allows to create a 3D mesh from the point cloud, using normal vectors, and produces a surface that cover the entire elevation and its outline. The third algorithm, *Automatic Contour (Cross Section)*, enables the user to define a cutting box around the cloud, generating and extracting the edges of the segmented point cloud. The output is 3D polylines in .dxf format, that can be flattened with a CAD software to calculate the surface area. The last method tested, described in (Nespeca and De Luca, 2016) and called “*Voxel Surface”,* suggests calculating the area by multiplying the number of points by the unit of surface, which is assumed to be planar and infinitesimal. For this calculation, the points must be uniformly distributed in 3D space, sampled with the uniform decimation, and the unit of surface must be approximated by a square shape. The first three tests involve an approximation of the 3D data captured in the acquisition phase, both if the point cloud is transformed into a mesh and if the cross-section plug-in is applied. On the other hand, the final procedure offers the advantage of calculating the area without converting the point cloud, thereby maintaining its accuracy; additionally, it requires less time and effort for data processing. For these reasons, we used this method to validate in a quantitative way all maps carried out through a semi-automatic point cloud segmentation process.

Soiling [m^2]	
Manual (blue)	Semi-Automatic (red)
13,61	12,40

Figure 8 Qualitative validation: comparison with the point cloud semi-automatically segmented (in red) and the area manually drawn (in blue). Below, the table shows the quantitative comparison.

Upon analysis of the results obtained from this work, it is evident that to validate the procedure, both quantitative and qualitative comparisons are required, as they provide complementary information on the extent and distribution of alteration/decay on the surface under investigation.
During the comparison phase, the proposed methodology demonstrates greater effectiveness and reliability in detecting three-dimensional alteration or decay. The results are generally positive, although human interpretation of the data is crucial, particularly in the case of colour-based segmentation. The resulting maps highlight critical areas requiring attention due to significant changes in colour status. However, information regarding the typology and causes of degradation cannot be obtained. For instance, to isolate areas affected by soiling, a map of points with the same colorimetric variation, probably caused by direct or indirect water exposure, was carried out. This condition can trigger different types of degradation, such as leaking or rising damp. Therefore, to accurately identify the cause of alteration/decay and provide an appropriate description of the phenomenon, it is essential to critically interpret the semi-automatic map.
Despite this disadvantage, one advantage of such a methodology is the ability to mine data related to the state of damage, including damage that is not visible or located in inaccessible areas. This is the case of the recognition of a 3D degradation in elevation. For instance, the (Fig. 9) clearly shows the out-of-plane displacement of a masonry portion in the south façade of the building (top left). As the terrace in front was inaccessible, the operators in the fieldwork did not record this deformation, which was too far away for a visual inspection. Instead, this phenomenon was effectively highlighted by the C2M (Cloud to Mesh) map obtained from the RANSAC Shape Detection plug-in. This process made it possible to obtain metric data regarding the extension on the plane of the façade and, in this case, also the measurement of the misalignment in the perpendicular direction. It is important to note that this tool is valuable for assessing the heritage state of conservation but also for gaining a deeper understanding of its historical evolution over time. The cause of this decay phenomenon has been attributed to the construction of the second elevation made in a later phase, using different type of masonry from the one used in the first phase, and probably not carried out in a workmanlike manner. [CM; RN; AM]

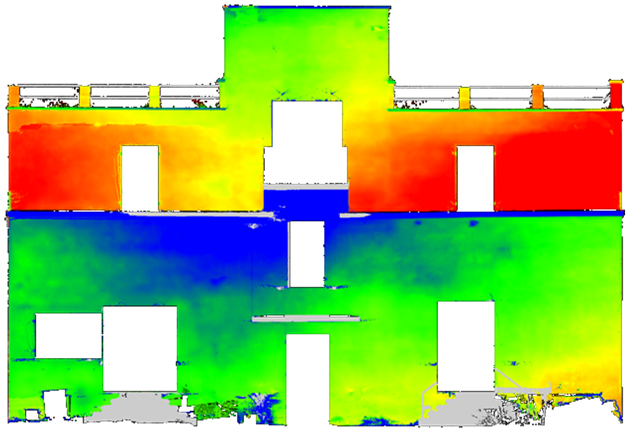

Figure 9 The C2M (Cloud to Mesh) map obtained by RANSAC shape detection plug-in, used to identify the scaling phenomena and its entity with a range from -9 cm (red) to +12 cm (blue).

5. CONCLUSIONS

The presented workflow fully leverages the integrated digital survey data, using them not only as a geometric reference for graphic representations but also for extracting additional information that enhances the semantic content of the HBIM.
One advantage of this work is the semi-automatic creation of 3D thematic maps that are directly compatible with the reference system of the digital replica and can be seamlessly integrated into its HBIM. Additionally, the geometry-based segmentations provide better alignment with traditional analyses and offer valuable information that may be difficult to obtain, such as identifying plaster bulges or structural misalignment on elevations. Taking advantage of remote sensing data capturing, the discussed data processing procedures offer a quick and non-invasive guide for determining where to conduct further, more expensive and invasive investigations. This result perfectly aligns with the principle of minimum intervention in heritage preservation.
On the other hand, the application of these advanced digital procedures requires specific know-how on the part of experts, whose critical reflection always plays a crucial rule. It is worth noting that scrupulous parameter selection is the basis for successful results in both data mining and point cloud segmentation. This is a disadvantage because some parameters need to be adapted to the case study and well interpreted by the operator, thus excluding a complete automation of the process. Obtained results allow for a comparative analysis between traditional and innovative digital methodologies, guiding towards a conscious integration of both while balancing their respective benefits and challenges.
In conclusion, the research demonstrates that semi-automatic segmentation tools can be valuable integration support for the interpretation processes of historical architectural heritage and, in turn, for the design of conservation strategies. Moving in this direction, to evaluate the replicability of the method, the authors propose to test the same procedures/tools on other case studies, with different architectural typologies, materials and states of conservation. [CM; RN]

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