SCAN-TO-MESHBIM: IMPLEMENTING KNOWLEDGE ABOUT HISTORICAL VAULTED CEILINGS WITH OPEN TOOLS

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Abstract

Accurate three-dimensional (3D) models for Heritage Building Information Modeling (HBIM) remain a significant challenge. This paper proposes a methodology that combines the Poisson Surface Reconstruction (PSR) technique with open-source management software to address this issue. The methodology uses automatically generated mesh models to produce reality-based 3D models of historical buildings. These models are enriched with geometric and semantic parameters according to BIM standards. The resulting methodology, Scan-to-MesHBIM, is an open 3D interface allowing experts to analyze and create a detailed set of properties adhering to construction rules.

To test the workflow, we selected two case studies of different vaulting types: the Renaissance barrel vault with cloister heads and lunettes from the Ducal Palace in Urbino (Italy) and the Gothic ribbed vault from St. André Cathedral in Bourdeaux (France). The use of implicit surfaces proved to be an efficient means for obtaining accurate 3D objects; then, the enrichment of the 3D models ensures a better understanding and more in-depth management in the field of Cultural Heritage (CH).

Keywords

Automatic Surface Reconstruction, HBIM, Historical vaulted system, Poisson, 3D mesh.

1. CHALLENGES OF HBIM METHODOLOGY

The use of Building Information Modeling (BIM) methodology within the frame of cultural heritage (HBIM) offers several advantages for enhancing the knowledge, conservation, and management of cultural assets [1]. There is a significant challenge related to the modeling process regarding historical buildings. Despite advancements in data acquisition techniques, such as digital photogrammetry or terrestrial laser scanning, which have improved the digitalization of historical buildings, complex architectural elements still pose a significant challenge in three-dimensional (3D) representation. It is well known that point clouds obtained with the abovementioned techniques offer a geometric support that facilitates both the 3D modeling and the generation of two-dimensional (2D) architectural drawings. However, the creation of accurate 3D reality-based models is significantly complicated by two characteristics: firstly, the use of non-standardized construction elements, and secondly, the existence of distortions in the structural elements. When a high accuracy level is

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required for the parametric 3D model, considerable time is needed to build up each element with all its singularities and shape deviations. Thus, a balance between the demanding modeling process and the reduction of the accuracy level is necessary to achieve an optimal 3D model representation. The pursuit of novel modeling strategies that maintain a proper accuracy level while minimizing the efforts required to obtain 3D models remains essential for the implementation of HBIM methodology.

Although successful workflows regarding HBIM are available in the literature [2, 3], most of them are based on proprietary authoring software, and a lack of shared standards for analysis and management is still noticeable. In developing HBIM objects, semantic segmentation of point clouds plays a pivotal role. Scan-to-BIM workflows, which are prevalent, generate parametric models grounded in reality and enriched with semantic knowledge. These models are crafted through multiple interpretation phases, employing solid or geometric surfaces based on the initial point cloud data.

A part of the debate, thus, contributes to automatizing some steps, speeding up procedures, and preserving data accuracy. In this line, the Poisson Surface Reconstruction (PSR) algorithm provides a fast and accurate workflow for the automatic generation of meshes from segmented points cloud and the reconstruction of complex geometries. Our research is focused on the automated generation of triangular meshes that preserve the geometric features of each element in historical buildings, enabling their use in an HBIM open environment. This novel approach is named “Scan to MesHBIM”.

This research exploits semi-automatic procedures for obtaining Building Objects Models [2]. In fact, according to the paradigm of object-based parametric modeling, the traditional Scan-To-BIM approaches are based on families generated in authoring software. Our approach enriches the detailed meshes with parameters and data related to the constructive and typological rules, making architectural objects semantically aware. The main contribution of the paper can be synthesized in a quite new method for carrying out reality-based models, automatically exploiting the meshes obtained from laser scanner data, semantically organized, and enriched via International Foundation Classes (IFC) management. Additionally, our Scan to MesHBIM approach involves open-source tools. The method is assessed in HBIM analysis of vaulted systems, including components such as lunettes, ribs, and decorative elements, which are considered fundamental parts of architectural complexes but have not yet been addressed with a sufficient level of detail.

Our research aims to improve the 3D modeling process for historical buildings, enabling their effective use within BlenderBIM [3] without losing some of their geometrical information and accuracy. The paper is organized as follows. A literature review is shown in Section 2 with a specific focus on the 3D meshing step, comparing the definition of implicit and explicit surfaces. Section 3 briefly describes the two case studies, followed by the presentation of the available points of cloud data. At the same time, the main paragraphs related to the methodology are the automatic surface reconstruction phase (Section 3.2) and the proper Scan to MesHBIM procedure (Section 3.3). Results with different kinds of explanation and discussion about IFC classes and obtained LOD and analysis carried out are presented in Section 4, followed by the future works.

2. LITERATURE REVIEW

The 3D digitization of built heritage is considered a pivotal phase in management and analysis but also for planning interventions: dense points cloud and high-resolution digital images can currently provide information for assessment of the state of conservation and risk of historical buildings [4, 5]. Photogrammetry can support the assessment of damages through 3D surface analysis and quantitative evaluation, as well as data about cracks, lack, and erosion on envelope surfaces through digital image processing [6].

The relatively new paradigm of HBIM (Heritage Building Information Modelling) shows extraordinary potential for the restoration process, especially if connected to cognitive automation. Some authors introduced different perspectives on HBIM modeling, with diagnosis and performance assessment as key aspects [7]. Others developed a "reverse engineering" approach for creating HBIM models of existing buildings, a watershed moment in its management. This method simplifies and organizes the information needed to preserve the existing architectural heritage while utilizing available resources [8]. Some works explored the accuracy of three-dimensional objects, such as vault systems, in terms of geometrical data, decay, and historical or stratigraphical analysis to inform future interventions [9]. The emphasis on Grade of Generation (GOG) and Grade of Information (GOI) during the interpolation of point clouds and model wireframes 3D objects [10] underscores the importance of possessing in-depth knowledge of the cultural asset before undertaking any action, as exemplified by the introduction of the Level of Knowledge (LOK) concept [11].

Following the critical issue of geometry data, Dynamo has emerged as a valuable algorithmic tool for comparing ideal geometry with reality-based models, facilitating the creation of 3D libraries [12, 13]. Although some works have tried to solve this problem related to the BIM format, IFC, and its schema, these proposals incorporate new IFC entities using Non-Uniform Rational basis splines (NURBS). Still, their applicability is limited to specific software [14, 15]. However, the manual development of these parametric 3D objects for comprehensive data analysis data can be time-consuming [16, 17]. NURBS and other Explicit Surfaces techniques [18] are more widely used in the field of HBIM than implicit surfaces. Still, the benefits of preserving geometrical features are considered the most suitable choice for testing surface-based reconstruction in a 3D documentation and analysis HBIM project.

An example of an implicit surface can be obtained by the Poisson Surface Reconstruction (PSR) algorithm, a robust and efficient method for reconstructing 3D surfaces from unorganized point clouds. PSR solves the differential Poisson equation, effectively fitting a smooth surface to the input point cloud data and obtaining sharp models [19]. An extension of Poisson that improves the over-smoothing problem is Screened Poisson Surface Reconstruction [20], but its integration in open-source software is still not so widespread. Utilizing deep neural networks as a geometric prior for surface reconstruction [21] addressed challenges such as overfitting artifacts and the approximation of sharp features, demonstrating better performance than existing reconstruction methods. The extraction of essential vertices is a significant step in working with complex geometries. An ordered statistic ranking criteria algorithm using Neuronal Networks (NNs) for the recognition of robust shape points was used in [22]. According to the current situation detailed before, our approach uses implicit surfaces, specifically the PSR algorithm, to capture the geometrical feature of Architectural Heritage in HBIM environments.

3. MATERIAL AND METHODS

The following paragraphs provide a detailed exploration of the materials and methodologies employed in our study. Two remarkable case studies were selected, each representing a specific period and type of vaulting system: Ducal Palace in Urbino (Italy) and St. André Cathedral in Bordeaux (France). Figure 1 synthesizes the tested workflow based on open tools: it starts with standard data processing followed by point cloud segmentation, automatic surface reconstruction, and the development of an HBIM procedure.

3.1 Preliminary analysis based on point cloud semantic segmentation

Table 1 represents the input data used in the present workflow, which came from different Terrestrial Laser Scanner acquisitions carried out using state-of-the-art procedures. Then, the data were processed according to a standard workflow in which alignment, decimation, and noise cleaning were implemented in the laser proprietary software Cyclone and Scene. Automatic surface reconstruction relies on density analysis because point density typically decreases according to the scan distance. Concerning this aspect, semantic segmentation was performed in Cloud Compare software to conduct a geometrical and typological analysis of the shape grammar: in our case, to classify the vaulted ceilings. According to widespread workflows in Scan-to-Bim, point clouds are usually semantically segmented to set up the 3D model hierarchy. To accomplish this segmentation, ontologies already developed in compliance with the Getty, Art & Architecture Thesaurus [23] were followed [24, 25]. As a result, the point clouds are segmented according to architectural elements with a density of point of 1 cm, a value that increases in some high and hidden areas as was described before. In our case studies, this situation affects the point cloud topography in different ways since the height and geometry presented in them are genuinely diverse. The data input for further steps consists of two different point clouds where ribs, lunettes, arches, and webs are distinguished to proceed with the 3D meshing step.

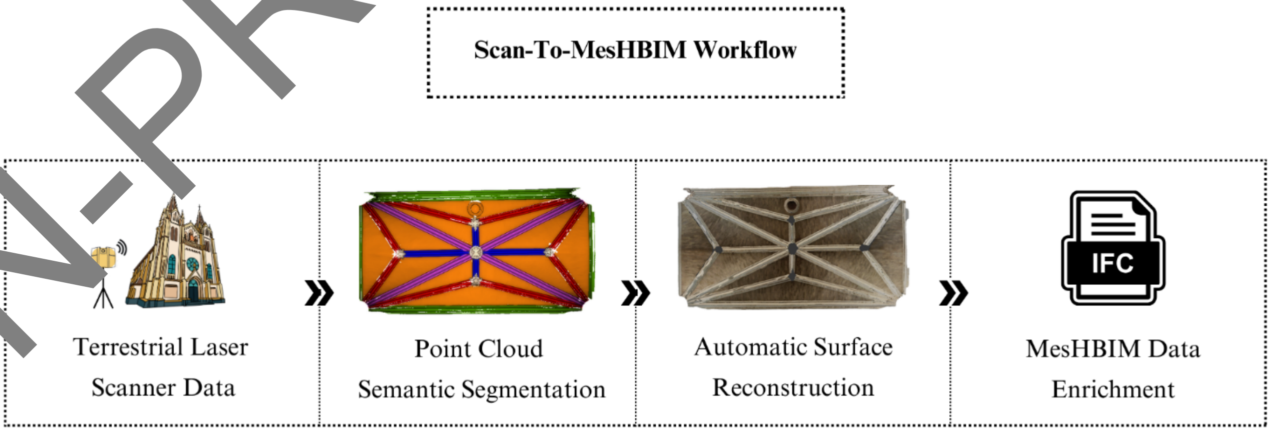


Fig. 1. Overview of the proposed workflow.

Location	Tool	Nº of scans	Total point cloud	Vault system points	Resolution
Urbino Ducal Palace *Guess Room* 06	Leica Geosystem P40	3	13.523.592	4.901.112	6 mm@ 10m
Cathedral of St. André Fourth Bay	FARO Focus S	3	8.548.996	5.559.218	6 mm@ 10m

Table 1. Dataset of the point clouds used in both case studies.

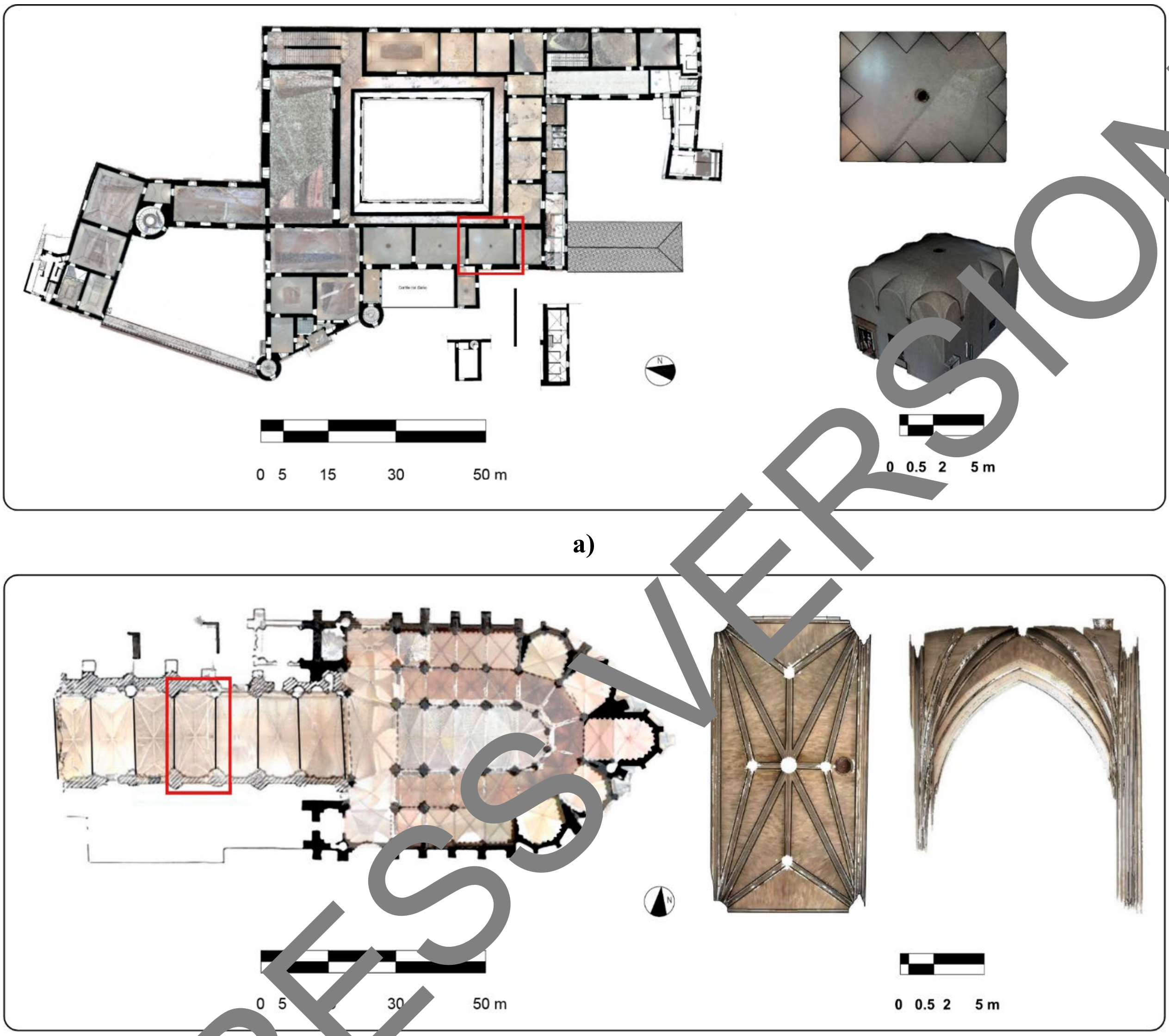
3.1.1 Case studies

The Ducal Palace in Urbino, currently housing the National Gallery of Marche, is a quintessential embodiment of Italian Renaissance architecture and art (Fig 2. a). Baldassare da Castiglione (1478-1529), an author and diplomat, characterized it as a "Palace in the guise of a city" [26]. This remarkable structure reached its zenith in the 15th century under the realm of Federico da Montefeltro, the Duke of Urbino. He engaged some of the most eminent artists of the era, including Luciano Laurana, Francesco di Giorgio Martini, and Donato Bramante, to craft exquisite architectural features, paintings, sculptures, and furnishings. These contributions transformed the Ducal Palace into a unique masterpiece of the Renaissance age, also presenting peculiar construction and typological solutions.

The "Piano Nobile" floor incorporates interesting geometry and constructional archetypal features of that historical period. This floor also houses the "Appartamento degli Ospiti" (or "delle Melarance") which dates back to the first phase of the floor. This intervention was carried out by Maso di Bartolomeo (1454 - 1464), who came from Florence as a scholar of Filippo Brunelleschi [27]. Our modeling procedure was implemented on a barrel vault with cloister heads and lunettes, a recurrent solution for classical palaces, not only during the Renaissance age. In this room, the directrix of the vault is a segmental arch, while lunettes are spheroidal: although a considerable curvature, it is a structural masonry vault.

Secondly, the St. André cathedral in Bordeaux is undoubtedly one of the city's most representative buildings of the Middle Ages and Early Renaissance (Figure 2. b). As usual, the currently existing construction is the product of several transformations that have taken place throughout the whole life of the building [28]. The origin of the cathedral dates back to the 11th century when the west end was built. During the 12th and early 13th century, the cathedral's nave was erected in Romanesque style. The building was enlarged from the end of the 13th to the mid-14th century by adding the transept and the polygonal apse using the Gothic construction system. In the 15th century, several restorations were made in the Romanesque nave, some of which affected the vaulting system. However, such works continued at the beginning of the 16th century, and new ribbed vaults were built covering the old nave. Some vaults added during the 15th and 16th centuries were quadripartite (with only two diagonal ribs inside them), while others included *tiercerons* and *liernes*, establishing a star vault.

Regarding our research, the ribbed vault of St. André cathedral, located in the 3rd bay from the east end, exemplifies late-gothic period constructions. Supposed to have been designed by Mathelin Gallopin during the first quarter of the 16th century, it is geometrically defined by semicircular diagonal arches, two slightly curved *liernes*, and pointed perimetral ribs, as well as the *tiercerons*, all arranged within a five-keystones schema.



a)

b)

Figure 2. a) Urbino Ducal Palace. Floor plan- *Nobile* (left). Ceiling and 3D axonometric view of *Guest Apartment* 06 (right). b) Cathedral of St. André: floor plan of the entire building (left). Ceiling and south elevation view of 4^{th} bay (right).

3.2 Automatic Surface Reconstruction

In response to the challenges outlined in Section 2, we have introduced the development of implicit surfaces to assess their performance in comparison to explicit surface techniques, which are used more often in architectural heritage. The data input for automatic 3D mesh generation is a semantically segmented point cloud described in Section 3.1. Open-source software offers many robust tools for 3D meshing, as described before. We opted to use the Cloud Compare software because it incorporates the Poisson Surface Reconstruction (PSR) algorithm, which typically employs a radial basis function (RBF) to represent the surface. The RBF can approximate a wide range of shapes, with the Gaussian function often chosen for its form:

$$f(x, y, z) = \exp\left(-\frac{x^2 + y^2 + z^2}{2\sigma^2}\right) \qquad (1)$$

where x, y, and z represent the coordinates of a point in three-dimensional space, and σ is a parameter controlling the function's amplitude [19].

PSR was selected due to its advanced surface reconstruction capabilities, which consider point density distribution values, transformed as a Scalar Factor (SF) that provides surface accuracy and supports the export of refined and confident geometry. This SF analysis is achieved by determining the proximity of the vertices of the reconstructed mesh to the input point cloud. Higher SF values indicate a higher density of points near the vertex. In comparison, lower values indicate a reduced density of points that can be removed or not considered (outliers removal process). In this case, density does not have a specific unit of measure, as it is a relative measure of the proximity of the points in the point cloud to each mesh vertex. Our approach uses points to define a volumetric scalar factor, whose level set between 0 and 0.[illegible] corresponds to the desired surface. The features of it depend on some parameters chosen before the 3D meshing. For instance, the octree value determines how the software algorithm divides the space into eight parts, which is crucial. An octree depth value of 10 was used for irregular or complex objects, indicating the number of subdivision levels. Another parameter is the number of sample points taken to create or define a node during the reconstruction process. After several tests, a point cloud density value between 10.00-15.00 was suitable. It's important to consider that according to the type of acquisition there is a variable density on almost all the point clouds. Lower sample point values create larger faces, which must be divided into more polygons, resulting in a 3D mesh with more faces. The point weight value chosen was 2.00, considering adequate the predefined value. As an additional step, quadric edge collapse decimation and random vertex displacement algorithms can serve as valuable tools for managing decimated 3D meshes, effectively addressing the limitations encountered in HBIM environments. In contrast, some authors have insight into suitable performance in terms of memory usage and processing time of PSR compared to other 3D meshing techniques in both large and small models. Concerning our case studies, the presence of elements of different sizes is another reason Poisson was chosen.

3.3 The Scan-to-MesHBIM procedure

In the final stage of this study, an HBIM approach was selected as an experimental method of analysis and management with a high Level of Development (LOD). A high level of geometry (LoG) was also achieved thanks to implicit surfaces obtained in the previous step. As a result, a new procedure, Scan-to-MesHBIM, was implemented and tested on complex vaults.

The first step consisted of identifying a specific HBIM environment lacking in optimizing the process. To address the handling of multiple OBJ files according to the semantic segmentation that requires our workflow, we integrated a Python script into the MesHBIM project. This functionality reduces time-consuming processes and simplifies their management. Secondly, data enrichment requires a preliminary and exhaustive architectural and historical analysis. A standardized reference has been incorporated to streamline this early HBIM phase. Since all the elements are defined according to the Getty, Art & Architecture Thesaurus, the custom script has been developed to incorporate a button link for facilitating relevant queries on ontologies or normative.

A crucial aspect of this process involves the annotation of geometrical and typological parameters, introduced in Section 3.1. *IfcPropertySets* was used to define these two specific sets of parameters to implement these requirements. IFC file templates are considered essential for data enrichment, implying efficient organization and interoperability with various software applications. Although the IFC 4 schema is chosen, it does not have classes explicitly tailored to vault systems. Therefore, existing IFC Classes have been used to verify their effectiveness in this scenario. For a comprehensive representation of components as lunettes or the entire list of ribs, which includes ridge, diagonal, and *tierceron* ribs, *ifcElementAssembly* effectively provides a hierarchical organization of elements. Furthermore, perimetral arches define the plan of the vault according to the construction rules, which is why *ifcBuildingElementPart* emerges as the most suitable choice for capturing their unique geometry and attributes. In both cases, remain geometry, webs, and intrados were considered as an *ifcSpace* according to the hierarchal approach. This distribution provides a robust framework for testing the applicability of these IFC entities in the context of this architectural typology (Figure 3). Finally, subclasses of *ifcSpace* were employed to establish two different typologies of vaults: barrel with cloister heads and gothic ribbed vaults.

Link tools were tested to integrate the 3D model with existing 2D documentation and analysis. In this way, the IFC Document can customize metadata for each element, allowing the association with specific floor plans, images, or tables. The geometrical analysis on the floor plan view was stored in *ifcSpace*, which is a suitable solution for integrating everything in the same workspace. Figure 4 shows the potential of the Urbino Ducal Palace HBIM project to achieve this objective.

Lastly, new investigations and drawings in Saint André Cathedral were incorporated into the annotation 3D view, enriching the overall knowledge by providing contextual information about geometrical analysis. This approach tackles verifying design hypotheses about the construction and applied geometrical rules (Figure 5). Including capabilities, in the present work, different workspaces were used to test the current state of 3D analysis. For instance, the floor plan in Figure 6 shows the geometrical analysis related to the distribution of *tiercerons* and keystones. The same figure also demonstrates the elevation plan of the tierceron rib where the radius and another analysis were performed.

4. RESULTS AND DISCUSSION

The methodology presented in this paper has successfully addressed achieving accurate 3D objects within the realm of HBIM. A balance between complex geometries, acquired data, and representation of 3D analysis has been established. Generating detailed 3D meshes via automatic surface reconstruction significantly streamlined the modeling process for intricate geometries and reduced point density areas commonly encountered in large-scale TLS-scanned buildings. The results show that all 3D objects obtained through PSR in the Ducal Palace case study can be used directly for analysis and management purposes, and successive postprocessing steps are not required. In the case of Saint André Cathedral, only keystone elements present some geometrical issues like holes and non-manifold faces due to the kind of acquisition carried out and the higher location of these elements regarding the scanner laser. In this case, some additional operations of filling and topology reparation are needed. Leveraging the PSR technique, we automated the generation of 3D surfaces via implicit surface models, a pivotal step in the Scan-to-MesHBIM proposed methodology. This approach seamlessly integrates with open-source management software environments such as BlenderBIM, facilitating the creation of reality-based 3D models for historical vaults and avoiding the presence of duplicated geometry, and finally entails less error and a higher LOG. The models are visually rich and imbued with geometric and semantic parameters adhering to BIM standards. The Scan-to-MesHBIM methodology, presented herein, culminates in an adaptable open tridimensional interface by utilizing free-form modeling software and enabling experts to create a comprehensive set of properties while allowing and facilitating geometrical analysis and potentially inferring construction rules. Its adaptability is demonstrated by some considerations: the open access code gives the possibility to improve the interface and the kind of managed data with simple coding skills. This customization empowers users to optimize the workflow based on different purposes of the modeling process as well as the specific features of the considered built heritage. The main advantage is, moreover, the data-enrichment adaptability, allowing to obtain models aware of relevant data tailored to specific project requirements, thereby enhancing the usefulness and relevance of the modeling outcomes (Figure 3). Furthermore, a high Level of Information (LOI) has been obtained, demonstrating the effectiveness of collecting data in case studies already investigated in many analyses and documentation processes, commonly in 2D. As a result, the Ducal Palace vault model is represented by its current irregular shape since they don't follow ideal circumferences or ovals (Figure 4).

On the other hand, the Saint André case study has been carried out with specific attention to experiencing the benefits that 3D analysis can offer to CH experts. Specifically, the distorted geometry of the vaults was preserved when creating the HBIM model, and the simplification that is almost always needed in the Scan-to-BIM traditional process was avoided. Even so, the design of the ribs has been analyzed using the current geometry of the net in its horizontal projection (Figure 5) and the elevations of the ribs (Figure 6). Such data is included in the model itself thanks to its high accuracy, and they can be detected and represented in the 2D projections (both in the horizontal one and in the elevations). As mentioned before, it is quite relevant when analyzing the geometric configuration of the ribs and the structural behavior of the entire vault. For this purpose, it is mandatory not to simplify the current geometry of the vault when creating the HBIM model.

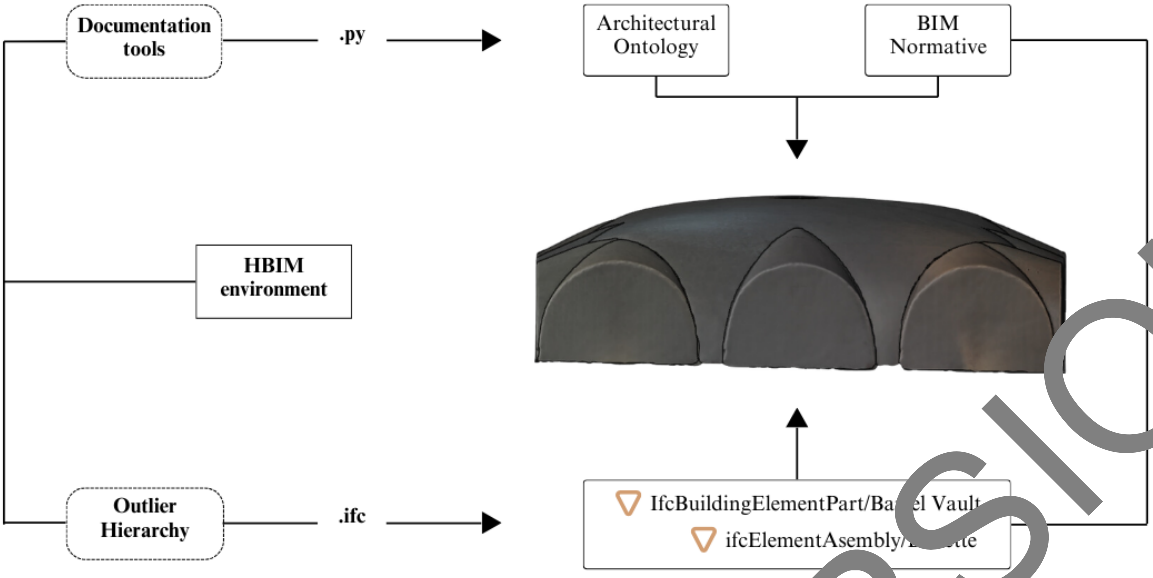


Fig. 3. HBIM proposal methodology. Ontology and IFC schema used for the Urbino Ducal Palace case study are integrated within the documentation improvements.

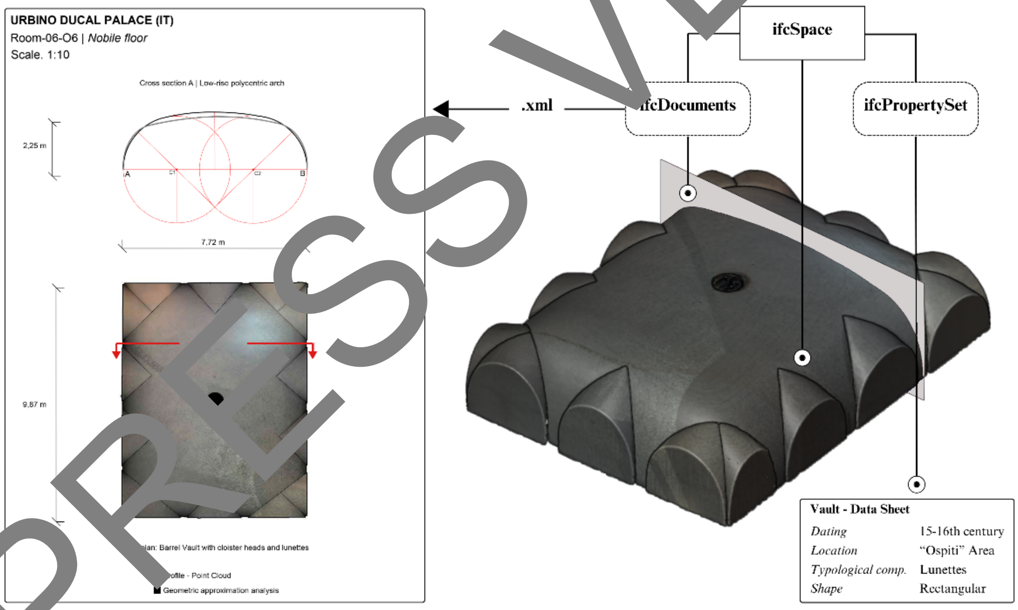
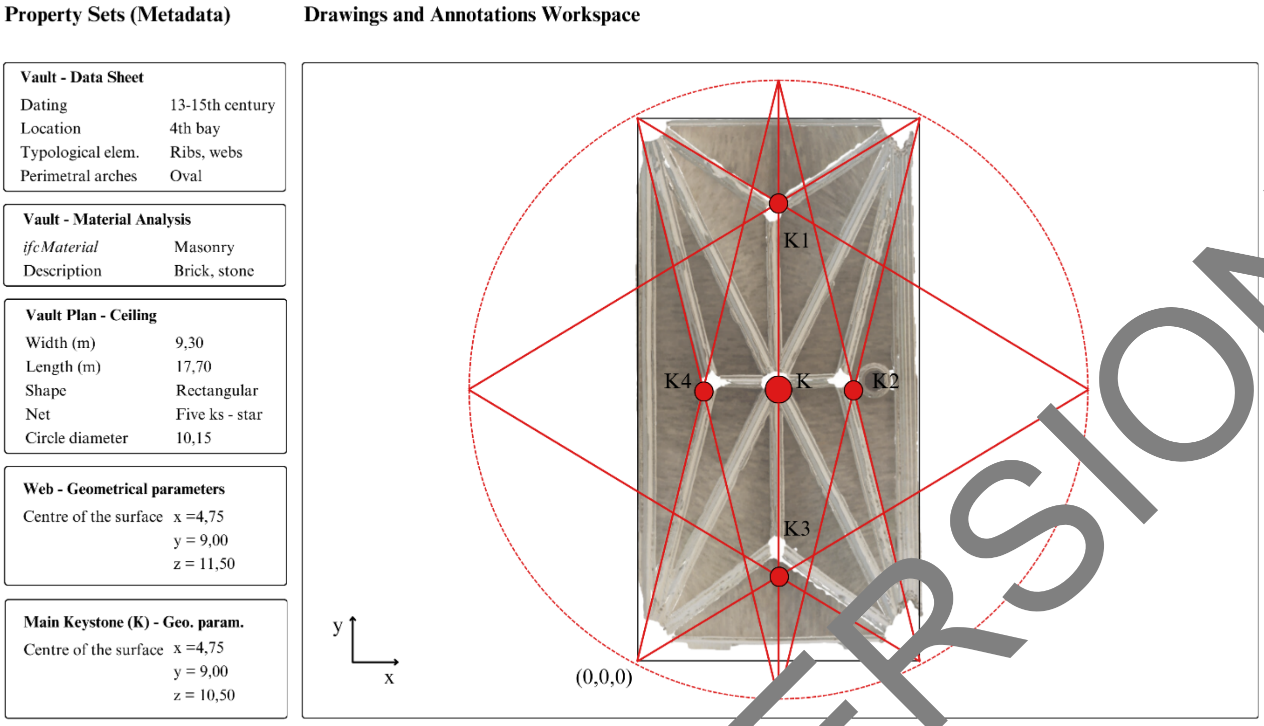


Fig. 4. 2D traditional analysis integration into an HBIM environment: the 3D model with a detailed IFC ontology application is associated with general *ifcpropertysets*.



Property Sets (Metadata)

Drawings and Annotations Workspace

Vault - Data Sheet	
Dating	13-15th century
Location	4th bay
Typological elem.	Ribs, webs
Perimetral arches	Oval

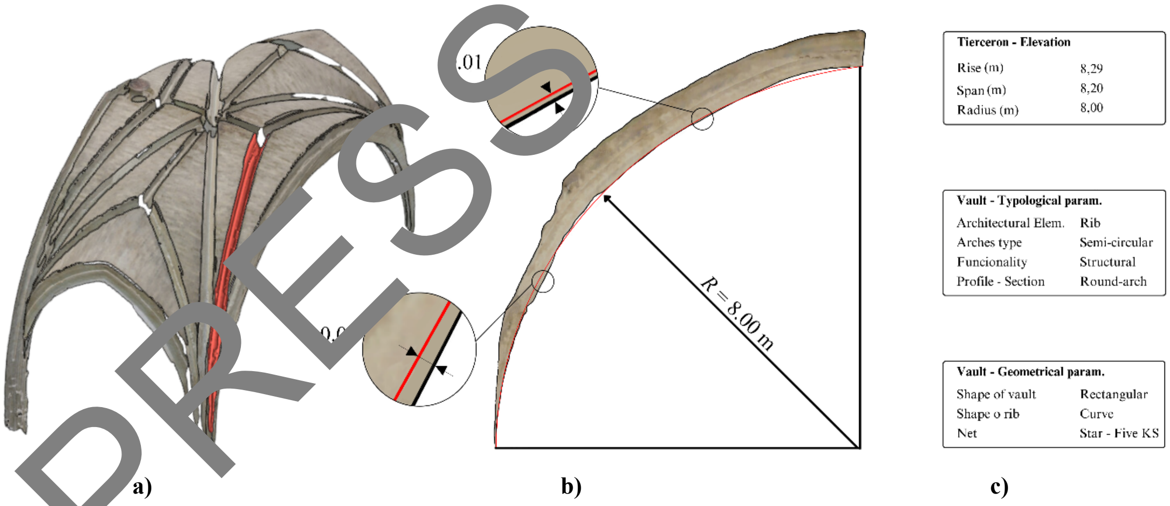
Vault - Material Analysis	
ifcMaterial	Masonry
Description	Brick, stone

Vault Plan - Ceiling	
Width (m)	9,30
Length (m)	17,70
Shape	Rectangular
Net	Five ks - star
Circle diameter	10,15

Web - Geometrical parameters	
Centre of the surface	x =4,75
	y = 9,00
	z = 11,50

Main Keystone (K) - Geo. param.	
Centre of the surface	x =4,75
	y = 9,00
	z = 10,50

Fig. 5. St. André Cathedral HBIM project. On the left, *ifcpropertysets* related to general and specific analysis. On the right, the ceiling plan view (intrados) with a geometrical analysis of the tracing and location of the ribs and keystones.



Tierceron - Elevation	
Rise (m)	8,29
Span (m)	8,20
Radius (m)	8,00

Vault - Typological param.	
Architectural Elem.	Rib
Arches type	Semi-circular
Funcionality	Structural
Profile - Section	Round-arch

Vault - Geometrical param.	
Shape of vault	Rectangular
Shape o rib	Curve
Net	Star - Five KS

a) **b)** **c)**

Fig. 6. 3D analysis of Saint André Cathedral: a) 3D general view with the analyzed tierceron highlighted, b) elevation view with the curvature analysis of such rib in BlenderBIM annotations tools, and c) tailored property sets of the same architectural element.

The training datasets selected in both cases, Ducal Palace of Urbino and St. André, are satisfactorily enriched for the 3D documentation and analysis in a BIM environment. The effort to preserve geometrical features in both buildings deals with the assumption that LOI and LOG obtained are proportional to LOD and each other. Following these achievements, Table 2 summarizes the entire process and results. In conclusion, this procedure is not focused on saving work time but on preserving the geometric information of the model. This point is critical within the restoration and conservation projects of historic buildings, where accurate data on the 3D objects (including their non-simplified dimensions and the possible distortions and structural movements) are essential.

Parameters	**Values**		**Description of parameters**
Processing	a	b	
TMS (hours)	2	4	Time required for manual segmentation
Relative SF	6.25	8.80	Range of relative density as Scalar Factor (SF)
TPSR+t (hours)	0.45	1.5	Time required for Automatic surface reconstruction and texturing
Output	a-b		
LOD	350		Defines the Level of Development of the BIM model components
LOI	400		Describes the Level of Information attached to a component in a BIM model
LOG	350		Establishes the Level of Geometric detail of the BIM model

Table 2. Processing and output parameters established for the HBIM project of a Historical Vaulted System, Urbino Ducal Palace (a) and Saint André Cathedral (b).

Our approach implies a significant change compared to emerged workflows in which the point cloud is used as a reference for parametric models [29]. [30] established a preliminary HBIM phase for restoration planning, and in [31] the potential of decay representation has been leveraged, demonstrating different levels of documentation and management. In our case, the taxonomy was managed for a significant part of the architectural hierarchical structure, and the final goal of the 3D documentation analysis was attained. Up to date, no workflows have been tested to study the typological features, analyze geometry, and infer the structural knowledge of architectural heritage with the same Level of Accuracy. The main advantages of our methodology are the following: a) the use of open access tool in an HBIM environment, b) an efficient management of optimized surface confidence (LOG) for complex geometries, c) the possibility to perform 3D analysis for different purposes and d) the readability of colorimetric features thanks to the preserved textures in IFC format. Within this, Figure 7 proposes a comparison with the Scan-to-BIM available workflows.

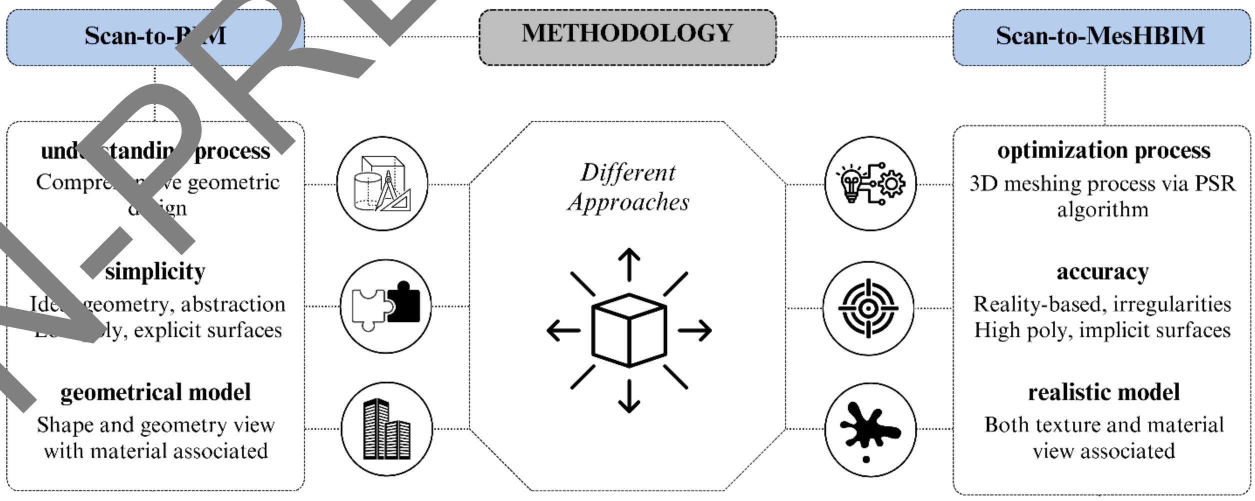


Fig. 7. Comparison of the current widespread Scan-To-BIM workflows and our procedure.

5. FUTURE WORKS

This research has demonstrated the potential of using implicit surfaces in HBIM environments for data enrichment, especially with high accuracy and without extra working time. Within geometrical and typological analysis already integrated, these HBIM projects tackle the improvement of specific analysis, such as identifying their historical and construction stages or studying their structural behavior, to establish a higher Level of Information (LOI). In this way, further works are being developed to implement the stratigraphic information obtained thanks to the methodology of the Archaeology of Architecture, that is, the data regarding the construction sequence of the several parts of the building. This approach is being implemented in the case study of the Basilica of San Isidoro (León, Spain), which has a rich and long sequence of buildings and transformations that dates back to the Middle Ages until the 20th century. Thus, we expect to create a model using the proposed Scan-to-MesHBIM methodology that automatizes the analysis and data enrichment of the whole data set related to its historical sequence.

Besides, these works allow us to make HBIM models consistent with their rules and complexity, thus implementing workflows that support the conservation and management of built heritage. In the case of other specifications, such as Level of Accuracy (LoA), future efforts should be focused on formulating a specific definition for Cultural Heritage, as the current specification is mainly centered on new construction parameters that require utterly different accuracy commitments. While IFC 4 enables the representation of vaulted systems through different *IfcElements*, several limitations are overlooked. For this reason, developing a new IFC specific to vault systems appears helpful in the context of HBIM methodology for better knowledge, conservation, and management of historical buildings. This necessity entails editing the IFC schema to develop new standards and classifications, thus implying a more extensive comparison with existing taxonomies and vocabularies.

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