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Streamlining FE and BIM Modeling for Historic Buildings with Point Cloud Transformation

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ABSTRACT

In this paper, a convenient workflow to obtain a simplified lightweight IFC description of a dense point cloud describing a historic building is proposed. The proposed procedure relies on slicing of the point cloud that aims at reconstructing the geometry of the solid. The resulting slices can then be easily employed in the generation of finite element (FE) and architectural building information modeling (BIM) models.In particular, the FE model generation procedure guarantees the obtainment of a conforming solid FE mesh ready to be used for structural purposes. Contextually, the architectural BIM model generation is achieved by slices extrusion to obtain the overall volume of the building. Then, the assembly of independent slice-based meshes is subjected to re-topology to obtain the overall watertight bounding surface of the building. A real historic structure is here used to show the effectiveness of the FE and BIM model generation procedures. Finally, the BIM model generation of an actual historic structure is carried out through the proposed workflow.

KEYWORDS

Masonry structures; interoperability; BIM; FEM; historic buildings; point clouds

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1. Introduction

In the last decades, increasing demand in Building Information Modeling (BIM) has been recorded in the Architecture, Engineering, and Construction (AEC) industry. In fact, a wide range of aspects, including energy efficiency and sustainability of buildings Sanhudo et al. (2018a); Lu et al. (2017a), safety in the construction process Martínez-Aires, López-Alonso, and Martínez-Rojas (2018a), and transportation infrastructures Costin et al. (2018a), have been explored.

While BIM processes have reached a reasonable level of maturity for new buildings, their implementation for existing assets is inhibited by challenges such as the high effort needed to convert captured BIM data into semantic BIM objects Volk, Stengel, and Schultmann (2014a). The endeavor is even more relevant if the attention is focused on existing buildings such as ordinary or historical masonry structures Vuoto, Funari, and Lourenço (2023b,a), regardless of the complexity of the asset to be modeled Bruno, De Fino, and Fatiguso (2018).

In the BIM application for documentation and conservation of historic buildings Murphy, McGovern, and Pavia (2009), modeling is typically tackled on the basis of survey data collected using photogrammetry and/or terrestrial laser scanning Yang et al. (2020). For instance, in Oreni et al. (2014), point clouds are first converted into parametric solid shapes and NURBS surfaces using Rhinoceros and Bentley Pointools software packages, and then converted into parametric objects in Autodesk Revit software. Yang et al. (2019) developed and applied a mesh-to-BIM modeling workflow based on Autodesk Revit and the visual programming tool Dynamo to a real case study. Moyano et al. (2021) discussed the application of a segmentation algorithm to classify the architectural components of a facade from the point cloud.

Another challenge to be tackled in BIM processes is the optimization of procedures for the structural assessment of historic buildings. For new buildings, Finite Element (FE) models can be generated in FE Analysis (FEA) software, starting from analytical models designed alongside the architectural counterpart in BIM authoring software Ursini et al. (2022). This approach might not be suited for historic buildings characterized by complex geometries, as highlighted by Ursini et al. (2022). Moreover, structural analytical models such as those provided in proprietary software or in the Industry Foundation Classes (IFC) collaborative standard do not allow the generation of FE models consisting of solid elements. Therefore, alternatives have been proposed.

For instance, Pepe, Costantino, and Restuccia Garofalo (2020) reconstructed surfaces from surveyed point clouds and then exploited them in BIM and FEA software for the generation of BIM and FE models. Barazzetti et al. (2015) simplified the geometry of a BIM model and meshed it to fulfill structural analysis requirements. Pirchio et al. (2021) exported an analytical model composed of approximated shell elements to an FEA software through an IFC file. Other approaches focus on the direct generation of an FE model from a point cloud.

Indeed, surveyed point clouds are a reliable data source for both architectural and structural modeling of historic buildings. In this context, several point cloud-based workflows for BIM and FE modeling lately developed for historic buildings highlight that the modeling choices made in the manipulation of the point cloud and in the subsequent generation of simplified geometry highly depend on the final purpose of the model, leading to compromises and time-consuming adjustments.

The incorporation of algorithms such as those proposed by Douglas and Peucker Douglas and Peucker (1973) for the reduction of the number of points required to represent a digitized line or its caricature, and advancements in technologies such as Scan-to-BIM Pepe et al. (2021), where digital management and representation in 3D GIS environments of cultural heritage sites can be achieved, further enhance the capabilities of BIM in managing complex geometries and historical data.

Moreover, standards such as the OpenGIS Implementation Standard for Geographic Information - Simple Feature Access Herring (2011) play a crucial role in ensuring interoperability and compatibility among different BIM systems and tools.

In the last decades, increasing demand in Building Information Modeling (BIM) has been recorded in the Architecture, Engineering, and Construction (AEC) industry. In fact, a wide range of aspects, including energy efficiency and sustainability of buildings (Sanhudo et al. 2018b; Lu et al. 2017b), safety in the construction process (Martínez-Aires, López-Alonso, and Martínez-Rojas 2018b) and transportation infrastructures (Costin et al. 2018b), have been explored.

While BIM processes have reached a reasonable level of maturity for new buildings, their implementation for existing assets is inhibited by challenges such as the high effort needed to convert captured BIM data into semantic BIM objects (Volk, Stengel, and Schultmann 2014b). The endeavor is even more relevant if the attention is focused on existing buildings such as ordinary or historical masonry structures (Vuoto, Funari, and Lourenço 2023b,a), regardless of the complexity of the asset to be modeled (Bruno, De Fino, and Fatiguso 2018). In the BIM application for documentation and conservation of historic buildings (Murphy, McGovern, and Pavia 2009), modeling is typically tackled on the basis of survey data collected using photogrammetry and/or terrestrial laser scanning (Yang et al. 2020). For instance, in (Oreni et al. 2014) point clouds are first converted in parametric solid shapes and NURBS surfaces using the Rhinoceros and Bentley Pointools software packages, and then converted into parametric objects in the Autodesk Revit software, in (Yang et al. 2019) a mesh-to-BIM modeling workflow based on Autodesk Revit and the visual programming tool Dynamo is developed and applied to a real case study, in (Moyano et al. 2021) the application of a segmentation algorithm to classify the architectural components of a facade from the point cloud is discussed.

Another challenge in BIM processes involves optimizing procedures for the structural assessment of historic buildings. While FE models can be easily generated for new buildings using FEA software, this approach may not be suitable for historic buildings due to their complex geometries (Ursini et al. 2022). For instance, geometrical models generated in BIM authoring software may fail to describe vaulted systems accurately and may exhibit node inaccuracies (Ursini et al. 2022). Additionally, commercial FE codes models often do not support the generation of models with solid elements (BuildingSMART 2018), necessitating alternative approaches.

Several alternative methods have been proposed. In some cases, surfaces are first reconstructed from surveyed point clouds and then utilized in both BIM and FEA software for model generation (Pepe, Costantino, and Restuccia Garofalo 2020). Other approaches implify the geometry of BIM models and mesh them to fulfill structural analysis requirements (Barazzetti et al. 2015), or export geometrical models composed of approximated shell elements to FEA software through an IFC file (Pirchio et al. 2021). Some approaches involve the direct generation of FE models from point clouds (Lucidi et al. 2021; Castellazzi et al. 2017; D'Altri et al. 2023).

Surveyed point clouds serve as reliable data sources for both architectural and structural modeling of historic buildings. However, the modeling choices made in manipulating the point cloud and generating simplified geometry depend heavily on the model's final purpose, often requiring compromises and time-consuming adjustments.

Furthermore, advancements in algorithms, such as those proposed by Douglas and

Peucker (Douglas and Peucker 1973) for point reduction, and technologies like Scan-to-BIM (Pepe et al. 2021), enhance BIM's capabilities in managing complex geometries and historical data.

The geometric accuracy is crucial for assessing structural behavior. Any discrepancies or inaccuracies can significantly impact analysis results (Eastman et al. 2011). Thus, the fidelity of FE analyses is inherently tied to the accuracy of the underlying geometric representation (Arayici et al. 2011).

Accordingly, the geometric model should faithfully represent the characteristics of the building to avoid misinterpretations of structural behavior (Becerik-Gerber et al. 2012). BIM's role in structural assessments extends beyond geometric representation, facilitating the integration of structural data with other features (Zhang and Teizer 2014).

This paper aims to optimise the workflows for FE and BIM modeling of historic buildings by proposing a novel transformation of point clouds into a structured BIM geometrical representation. The key aspect of the procedure is the practical simplification of the point cloud in two-dimensional objects stored in the IFC file format. These objects can serve as a data source for both FE and architectural BIM modeling purposes.

It is worth to highlight that the paper focuses on BIM modeling utilizing open-source tools, e.g., Blender. Accordingly, this requires special learning efforts and specific challenges by the users (compared, e.g., with traditional and widespread commercial BIM authoring software)

The paper is organized as follows. In Section 2, the description of the procedure which starts with a point cloud and returns a simplified version of it in the IFC format is provided. In Section 3, the IFC description of the point cloud is employed for the generation of a FE model and of an architectural BIM model of a building prototype by means of open-source software. In Section 4, the procedure is applied on the point cloud of a real Cultural Heritage (CH) building. Some concluding remarks end the manuscript.

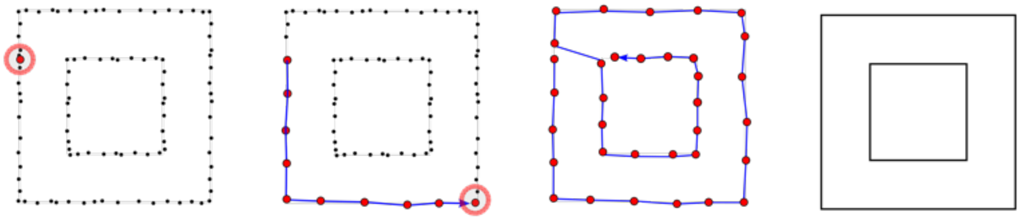
2. From point clouds to IFC slices

2.1. *Geometry description through slices*

When dealing with existing and historic buildings, typically characterized by complex shapes, the geometry description through slices appears particularly convenient. In fact, the slicing of the geometry along with the vertical direction appears especially suitable (Castellazzi et al. 2015), as it follows the natural construction phases.

This idea has been formerly exploited in the Cloud2FEM procedure (Castellazzi et al. 2015)(Bitelli G. and Castellazzi G. and D'altri A.M. and De Miranda S. and Lambertini A. and Selvaggi I. 2016), which enables the direct utilization of dense point clouds for the generation of continuum voxelized 3D FE models through slicing (Castellazzi et al. 2017). In particular, the Cloud2FEM procedure briefly relies on the definition of N slicing planes at sequential (increasing/decreasing) heights $[h_1, h_2, ..., h_i, h_i + \Delta_h, ..., h_N]$ (with regular or irregular distance gaps Δ_h) that enable the creation of N 2D surfaces (solid slices) of the area occupied by the structure at a specific height. The creation of solid surfaces is of course possible only when inner and outer surface scans of the structure are available to define concave/convex hull borders (Castellazzi et al. 2015, 2017). Then, once the definition of the N slicing surfaces is obtained, the stacking sequence of voxels is mastered by the simple definition of a $3D$ spatial grid where the z intervals are set according to the sequential heights definition, and the (x, y) intervals are set according to the structure dimension or the target mesh size $[H_x, H_y]$ the user would like to set. In this regard, the selection of specific $[H_x, H_y, \Delta_h]$ enables the automatic defeaturing of the structural model since objects with smaller dimensions than $\min([H_x, H_y, \Delta_h])$ cannot be properly described and then are automatically eliminated in the definition of the FEM model.

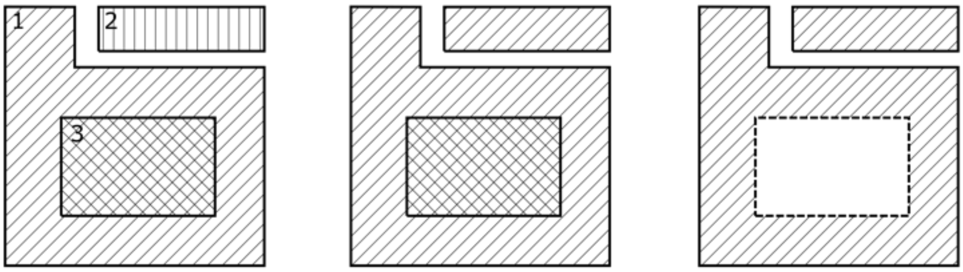
A recently proposed Python-based implementation of the Cloud2FEM procedure favors a convenient workflow (Castellazzi et al. 2022). More in detail, its graphical user interface allows it to automatically perform the following operations: slicing of a point cloud in N slicing planes, generation of polylines and their quality improvement by the Douglas-Peucker algorithm(Douglas and Peucker 1973), classification of interior and exterior boundaries, generation of a 3D voxelized FE mesh. Moreover, manual adjustments can be performed to solve inconsistencies due to the uneven density of the point cloud or those resulting from the scanning of unwanted portions, such as vegetation or furniture inside buildings. A schematic representation of the automatic generation of polylines for a given slice of a point cloud is shown in Figure 1.



(a) (b) (c) (d)

Figure 1.: Polylines automatic generation and quality improvement performed by means of the Python-based Cloud2FEM implementation (Castellazzi et al. 2022): point cloud section at the onset of the procedure (a), intermediate phase of the procedure (b), complete generation of the unique raw polyline (c), clean polylines after splitting and noise reduction (d).

Figure 2 illustrates the automatic recognition of interior and exterior boundaries by means of iterative Boolean operations. The final result in Figure 2(c) consists of a unique Multi-Polygon object Herring (2011), i.e. a data structure that describes the set of exterior boundaries with the corresponding interior boundaries (if any). Another key feature of the Python-based implementation of Cloud2FEM is its ability to store all the processed data by means of a persistent dictionary-like object.

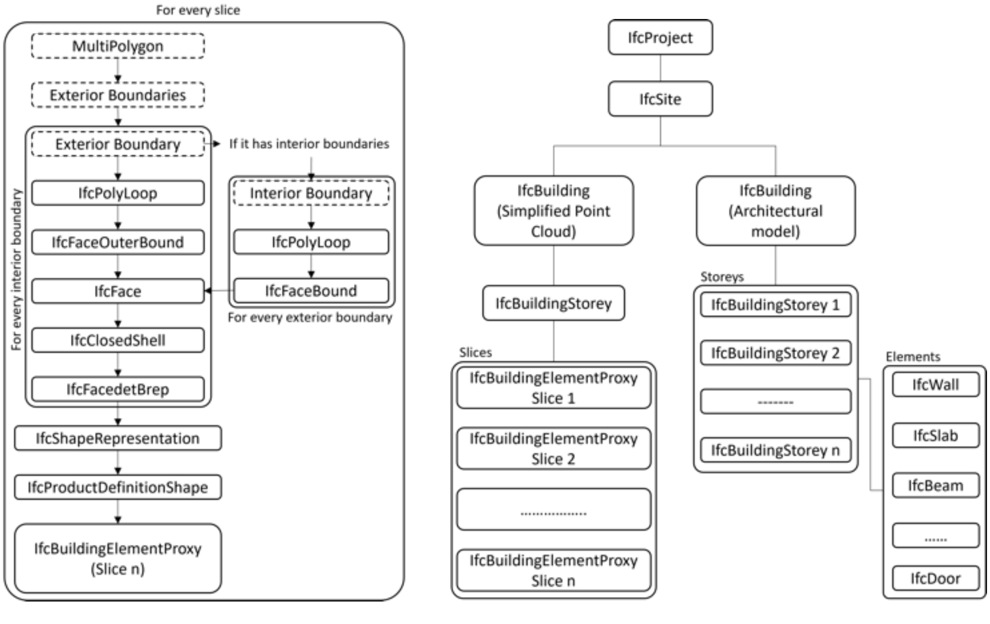


(a) (b) (c)

Figure 2.: Generation of a Multi-Polygon through iterative symmetric difference operations performed by the Python-based Cloud2FEM implementation (Castellazzi et al. 2022). Initial boundaries (a), first iteration i.e. symmetric difference between boundaries 1 and 2 (b), second and final iteration i.e. symmetric difference between the Multi-Polygon obtained at the previous step and the boundary 3 (c).

2.2. *IFC definition: slice conversion*

The persistent dictionary-like object delivered by the Python-based Cloud2FEM (Castellazzi et al. 2022) contains N lightweight Multi-Polygons, derived for the corresponding N slicing planes placed at sequential heights $[h_1, h_2, ..., h_i, h_i + \Delta_h, ..., h_N]$, which can be easily manipulated in a Python environment. However, it cannot be directly used within a BIM environment since the adopted Multi-Polygon data structure is not conceived in BIM data standards such as the well-known IFC (BuildingSMART 2018). Therefore, an original conversion into the IFC format is proposed here to foster the collaborative definition in the BIM environment. The conversion is described in Figure 3a. From the Multi-Polygon slices, each exterior boundary is converted into a IfcPolyLoop. Then, every IfcPolyLoop will support the definition of a IfcFaceOuterBound. In the case of interior boundaries, a further IfcPolyLoop will be created to support the definition of IfcFaceBound.



(a) (b)

Figure 3.: Conversion of a Multi-Polygon into an Ifc element: slice generation (a); Ifc structure (b).

The combination of IfcFaceBound and IfcFaceOuterBound will then provide the IfcFace objects to support the definition of IfcClosedShell and IfcFacetedBrep. This procedure allows for the correct definition of a IfcBuildingElementProxy that is the entity to be used to exchange special types of Building elements (slices) for which the IFC standard does not provide a semantic definition. The set of IfcFacetedBrep obtained from the conversion of the Multi-Polygon is therefore adopted to define the IfcShapeRepresentation of the slice, which contained in the IfcProductDefinitionShape constitutes the representation of the IfcBuildingElementProxy.

Once the conversion of the whole set of slices is completed, the result is a simplified point cloud composed by a respective set of IfcBuildingElementProxy items, which still need to be placed in the spatial project structure of the IFC schema. The solution which allows achieving a clean separation between the simplified IFC point cloud and an architectural model stored in the same IFC file is shown in Figure 3b. All slices are spatially contained in an IfcBuildingStorey, to which are related using the IfcRelContainedSpatialStructure relationship. The storey is contained in the IfcBuilding (simplified point cloud), which is in turn contained in an IfcSite. On the other hand, the synthetic representation of the architectural model shows the standard IFC structure composed of elements spatially contained in different storeys, held by the appropriate IfcBuilding. The above-mentioned procedure was implemented by means of a Python (Van Rossum and Drake 2009) script, adopting the open source libraries Shapely (Gillies et al. 2007) and IfcOpenShell (IfcOpenShell 2020) for Multi-Polygon and IFC entities manipulation, respectively. As will be shown in detail in Section 3, besides the more evident purpose of the conversion of slices into the IFC format for the storage of a lightweight simplified point cloud (in a collaborative file format) and to support the architectural BIM modeling, the presented IFC point cloud can also be utilized as a data source for the generation of FE models.

3. Exploitation of the simplified IFC point cloud for FE and architectural BIM modeling

In this section, two case studies of the simplified IFC point cloud procedure presented in Section 2.2 show its possible adoption as the unique data source for the generation of a FE model and a BIM architectural model (see Figure 4).

A synthetic building prototype is here introduced (Figure 5a), as it will be conveniently used in the following to highlight the main developments carried out in this research. The building prototype is designed to include typical features of an exist-

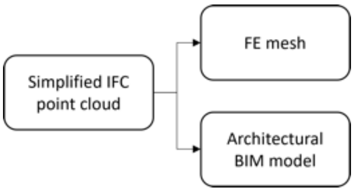


Figure 4.: Use case examples of the simplified IFC point cloud.

ing/historic masonry building, e.g. irregular building shape, geometrical imperfections, arbitrarily curved surfaces, irregular openings, etc. Building plan dimensions are approximately 8 by 8 meters, with 12 meters in height at the top of the domed structure. Wall thickness ranges from 0.5 to 1.0 meters and floors are interrupted by a staircase. Openings are characterized by different shapes.

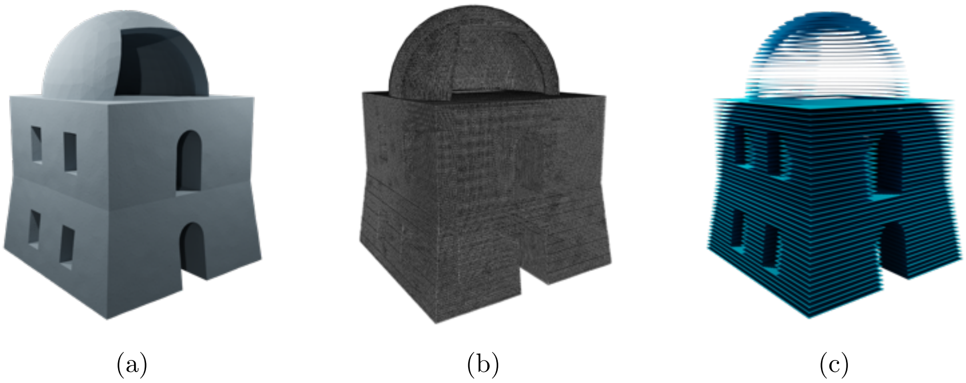

(a) (b) (c)

Figure 5.: Building prototype: Blender model (a); synthetic point cloud (b); simplified IFC point cloud (c).

This building prototype was modeled using the Blender software (Community 2018). Some artificial imperfections were added to simulate the typical building irregularities, namely: (i) lack of verticality, (ii) curved surfaces, and (iii) variable thickness. Moreover, the introduction of a random noise mimics the potential precision acquired during the scan of a real building. A synthetic point cloud (Figure 5b) is extracted over the building geometry throughout the definition of a Triangulated Irregular Network (TIN) mesh of the geometry surfaces, with an average distance between vertices of about 5 millimeters. It was then processed according to the approach exposed in Section 2, which gave as a result the simplified IFC point cloud displayed in Figure 5c.

3.1. *FE model generation*

This section illustrates how a simplified IFC point cloud can be employed as a geometric data source for the generation of a discretized geometry such as a solid FE mesh.

Once the IFC point cloud has been generated, it is possible to proceed with the FE model generation. To do that, the Cloud2FEM procedure (Castellazzi et al. 2022) is here considered. Indeed, the user could directly use the inborn Cloud2FEM procedure since the present method and the Cloud2FEM procedure stems from the same idea: the simplified IFC point cloud is a set of bi-dimensional geometries, which can be converted into a set of Multi-Polygons and stored in turn in a dictionary-like object, that can be directly used with the Cloud2FEM procedure.

This conversion could be simply described by reading the flowchart in Figure 3 from right to left. In fact, it can be performed by following backward the steps of the procedure, i.e. given an IfcBuildingElementProxy slice, the geometric data is retrieved and finally converted into a Multi-Polygon entity, which can then be stored in a dictionary-like object together with its corresponding vertical coordinate. Then, the grid-based mesh generator of the Python-based Cloud2FEM is adapted to generate a 3D voxelized FE mesh. Every slice is ideally overlapped with a custom grid whose spacing dimension is set by the user according to the dimensions of the structural features (Figure 6). Accordingly, each grid unit will correspond to a finite element. Indeed, the original key idea of the Cloud2FEM procedure (Castellazzi et al. 2015) is to decompose the volume of the building into slices and to decompose every single slice into a summation of regular rectangular areas that possess the same horizontal and vertical organization, see Figure 6a. Then, aiming at the definition of exact stacking sequence, the occupied areas will not change size or alignment regardless of the real position of the outer border of the slice, when moving from slice to slice. This practical raw discretization allows for the logical subdivision of the space occupied by the structure, through the definition of a simple topology and element connectivity. At the generic $i-$th slice, rectangles whose upper level $(i+1)-th$ is empty will not generate finite elements (see area highlighted in blue in Figure 6b). Conversely, rectangles whose upper level is filled will generate a hexahedral 8-node finite element, see Figure 6c.

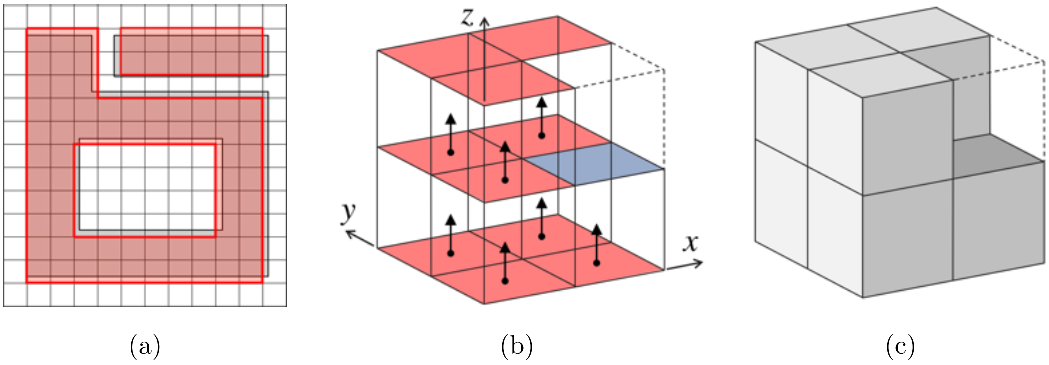
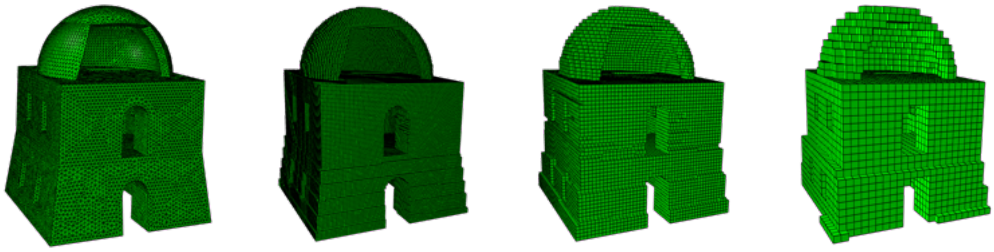


Figure 6.: Grid-based FEM model generation: example of a Multi-Polygon (in gray) and the resulting arrangement of finite elements (in red) for the i-th slice (a); 3D reconstruction of the FE mesh (b); resulting grid-based FE mesh (c).

The IFC-based FE model generation procedure is herein applied to the building prototype described in Section 3. The starting point is the simplified IFC point cloud shown in Figure 5c, which is then converted into a dictionary-like object and loaded into the Python-based Cloud2FEM implementation. Depending on the slicing step and grid spacing selected by the user, it is possible to obtain several FE models with different volume approximation levels. In this case, geometry discretizations with $10 \times 10 \times 10cm$, $20 \times 20 \times 20cm$, and $40 \times 40 \times 40cm$ voxels were considered, see Figure 7. In particular the $10 \times 10 \times 10cm$ model employs 120 slices and a $10 \times 10cm$ spacing grid, the $20 \times 20 \times 20cm$ model employs 60 slices and a $20 \times 20cm$ spacing grid, while the $40 \times 40 \times 40$ model employs 30 slices and a 40×40 cm spacing grid. As a result, volume errors in the range 0.06 % - 3.53 % were obtained when comparing the reference geometry (CAD model) with the voxel-based generated ones (Figure 7). It is worth noting that these voxel-based models were obtained by applying the procedure shown in Figure 6, without post-processing the volume surface with smoothing or projection techniques.

To further assess the voxel-based model quality, FE natural frequency eigenvalue analyses were performed (Figure 7) and compared with the reference model. Particularly, the reference model is then meshed through tetrahedral four-node elements in order to overcome the complexity of the reference geometry. The first natural modes of vibration of the voxel-based models are compared with the one of the reference model in Figure 7, where also the frequencies and relative errors are collected. As it can be noted, the frequency error of the voxel-based models slightly increases by coarsening the mesh, although always smaller than 4%, i.e. acceptable for structural analysis purposes.

A significant outcome of the proposed procedure is the fact that the simplified IFC point cloud can also be seen as a lightweight geometrical model stored in a BIM-friendly file format, ready to be used to generate a 3D FE model for structural assessment. Moreover, this kind of simplified model allows high user flexibility, where the refinement of the FE mesh can be simply performed by adjusting the grid size or neglecting some of the slices. It has to be pointed out that while the IFC standard has the capability to define structural analysis models (IfcStructuralAnalysisModel), they are rarely used by BIM and FEA software packages, and only conceive the definition of mono and bi-dimensional elements (IfcStructuralCurveMember and IfcStructuralSurfaceMember, respectively). Therefore, the proposed approach could be an interesting starting point for the definition of an IFC structural model for solid FE models.

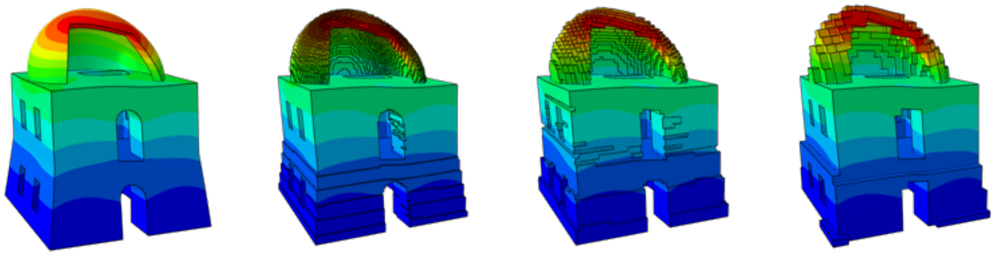


(a) Reference model $V = 417,87m^3$

(b) Model 1: $10 \times 10 \times 10$ $V = 417.6m^3[e = 0.06\%]$

(c) Model 2: $20 \times 20 \times 20$ $V = 416.31m^3[e = 0.37\%]$

(d) Model 3: $40 \times 40 \times 40$ $V = 432.64m^3[e = 3.53\%]$



(e) $\lambda_1 = 9.90Hz$

(f) $\lambda_1 = 9.67Hz$ $[e = 2.32\%]$

(g) $\lambda_1 = 9.55Hz$ $[e = 3.54\%]$

(h) $\lambda_1 = 9.52Hz$ $[e = 3.84\%]$

Figure 7.: Natural frequency analysis. Comparison of the first mode of vibration between the voxel-based models and the reference model. Clamped boundary conditions were considered for nodes located at the ground level, while 1500 MPa, 0.2, and 1800 kg/m^3 were assumed as Young's modulus, Poisson's coefficient, and density of the material, respectively.

3.2. *Architectural BIM model generation*

In this section, we present the architectural BIM model generation procedure based on a simplified IFC description of the point cloud through slices. The building prototype presented in Section 3 is here considered.

Given the collaborative nature of the IFC file format, the simplified IFC point cloud can be directly employed in several commercial software packages to serve as a lightweight geometry representation of the surveyed structure. Depending on the capabilities of the adopted software and the preferences of the modeler, the generation of an architectural model can be accomplished by following various modeling strategies. Here, the Blender (Community 2018) software, supported by the BlenderBIM (BlenderBIM 2018) Add-on, is employed, but any other software with similar capabilities could be used for this purpose. Once the simplified IFC point cloud is opened in the Blender environment, the whole set of 2D slices is extruded in the vertical direction, leading to a stack of 3D geometries (thick slices) as shown in Figure 8a. Subsequently, the stack of 3D geometries could be merged and discretized as a 3D mesh, obtaining a watertight mesh object representing the overall shape of the building (Figure 8b). These first two steps require very little time to be performed due to the robustness of the simplified sliced initial geometry. At this point, if needed, the mesh in Figure 8b can be partitioned into semantic parts (such as walls or floors) according to the architectural or structural features of the building (Figure 8c) and also simplified into regular shapes or smoothed (Figure 8d) to eventually achieve a convenient conventional representation of the architectural model (i.e. adding or removing as usual for BIM aesthetics/architectural features). The central point here is the ability to get a geometric representation of the entire building (Figure 8b) in an efficient way, while the further processing of the geometric data highly depends on the final purpose of the BIM model as usual for scan-to-BIM procedures. Regarding the modeling steps in the Blender-BlenderBIM environment, it has to be pointed out that the geometric and semantic aspects of objects can be managed separately, therefore a mesh can be freely manipulated and semantic properties can be assigned once the geometric counterpart is set according to the scope of the BIM model.

A simplified quality assessment of the achieved geometrical accuracy of the BIM model geometry can be performed by graphically overlapping the latter to the reference synthetic point cloud, as illustrated in Figure 9a. It has to be pointed out that

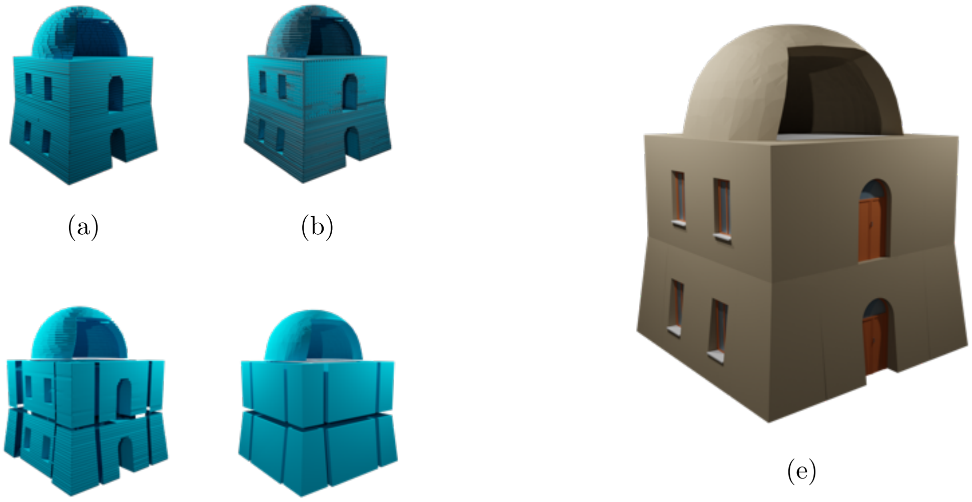
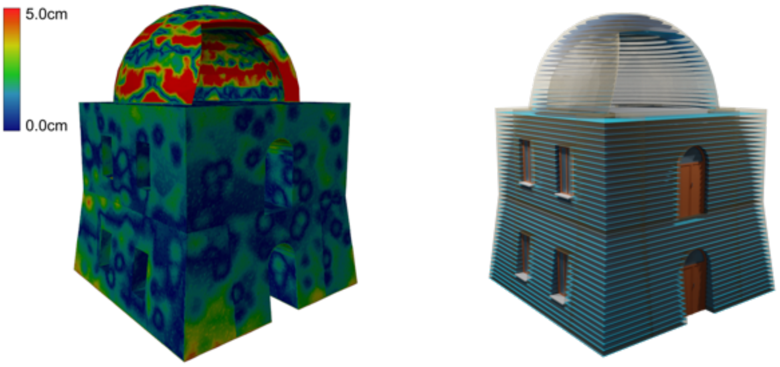

(a) (b) (c) (d) (e)

Figure 8.: Generation of the architectural BIM model. Closed polygon slices extruded (a), re-topology of boundaries surfaces (b), watertight partitioning of the geometry using primitive geometry to enhance the semantic enrichment (c), convex-hull of primitive geometry (optional) (d), final architectural BIM model (e).

in this case the slicing is carried out by considering a constant distance between slices throughout the whole height of the prototype. Nevertheless, a reduction of the distance between slices, where needed, e.g. at the curved surfaces, can easily lead to an important reduction of error. A further comparison could be performed by using the final BIM model geometry (Figure 8e) and the simplified point cloud (Figure 5c). In this case, a very small approximation is recorded, with an error order of magnitude around 0.1 cm in regions with planar boundary surfaces at maximum equal to 5.0 cm in regions closed by curved surfaces, see Figure 9a. Of course, a loss of geometric accuracy of the order of 5 cm might seem significant, and it could be too coarse for geomatics purposes. However, when dealing with structural analysis of large-scale cultural heritage structures such geometric error might be negligible, given also the large uncertainties in the material characterisation, construction details inside structural components, ageing of the materials, etc. Accordingly, the utilisation of the slicing technique (Figure 9a) has potentially a wide application field. It must be pointed out that the obtained geometry does not conform to a specific family object; it could be referred to as a mass in common terminology. Therefore, this geometry represents a generic, non-parametric 3D form that can be used directly for conceptual design,



(a) (b)

Figure 9.: Comparison between point cloud geometry and BIM model (a), superposition of the complete model and the slices in a BIM authoring environment (b).

spatial analysis, and visual representation within the BIM model. To convert it into a component that can be part of a family, the user can follow the usual general steps depending on the software used: adapt the geometry (scaling, trimming, partitioning), define parameters, and then save the family. An example of this procedure will be exploited in the next section.

4. Application to a real case study

To test the architectural BIM model generation effectiveness, an application to a real case study is presented in the following. In particular, the San Felice sul Panaro fortress was herein considered (Figure 10a). Such fortified structure was hit by the Emilia Earthquake (Italy) in 2012 with two main shocks, which occurred on 20th May (moment magnitude MW = 5.86) and on 29th May (MW = 5.66) (Scognamiglio et al. 2012). Such historic building is characterized by complex structural and architectural features due to several remodeling stages over several centuries, plus the complex geometry resulting after some partial collapses occurred during the seismic events, see Figure 10b.

A detailed survey was performed after the seismic events using a FARO Focus 3D laser scanner and a total station Trimble S6. Numerous targets were then placed, for both the exterior and the interior of the fortress, to allow for precise identification of tie points between scans. A closed polygonal topographic network was prepared, to detect the position of each target using the total station, allowing for a proper position calculation and adjustment. Subsequently, 163 point clouds were acquired by different scanning positions using the laser scanner. These scans were aligned to the topographic network through correlation with the reference targets. The resultant survey achieved a precision level of approximately one millimeter. Then, the aforementioned clouds were merged into a unique cloud containing approximately $3 \cdot 10^9$ points, see Figure 10b. A sub-sampling of the original point cloud was applied, reducing the initial dimension and enforcing a regular spatial sampling of 0.005 m, to manage it in further analysis.

In this application, the attention is focused on the North tower of the fortress, severely damaged by the earthquakes. Accordingly, the portion of the point cloud related to this tower, composed by approximately $60 \cdot 10^6$ points, is extracted. Using this initial data set, the procedure recalled in Section 2.1 is applied, which allows obtaining a geometrical description consisting of 84 slices with $h_i = 0.20m$, of which five representative slice locations are highlighted over the structure in Figure 10c and further illustrated in Figures 10d-10h by means of point cloud extraction at specific height h. Then, the original point cloud (Figure 10i) is processed to obtain polylines (Figure 10j), and the final regularized clean MultiPolygons Figure 10k).

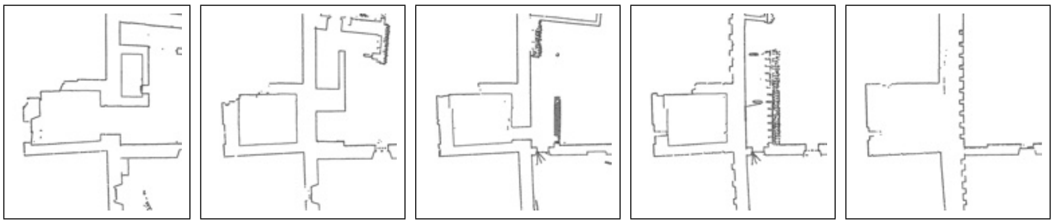
It is worth mentioning that some manual cleaning operation is needed during the cloud manipulation, due to the presence of debris and the noise caused by plastic tarpaulins used to cover the collapsed upper parts of the tower. The entire set of MultiPolygons, stored in the dictionary-like object, is then processed through the procedure proposed in Section 2.2 to obtain the simplified IFC point cloud (Figure 11a). Then, the architectural model generation of the real case study reflects the steps described in Section 3.2 for the building prototype, passing through the extrusion of the whole set of slices (Figure 11b), the remeshing phase to get the watertight boundary surfaces (Figure 11c), and an eventual subdivision in semantic portions as shown in Figure 11d. The versatility of the Blender-BlenderBIM environment allows to obtain an IFC file structure that reflects that represented in Figure 3b, where the simplified point cloud and the architectural model coexist in the same file, ready to be directly imported within commercial available BIM software (see Figure 12).

A geometric validation was performed by comparing the mesh obtained by the proposed procedure (solid definition) with the original complete point cloud. Cloud Compare software was employed using the Cloud-to-Mesh (C2M) distance function as shown in Figure 13b. The results of the comparison between the point cloud and the mesh show that the distribution of most points is within a range of ±0.03 m with a standard deviation value of 0.028m excluding the points whose distance is larger than 0.1 m highlighted in red color in Figure 13a, since these points correspond to portions that were not modeled.

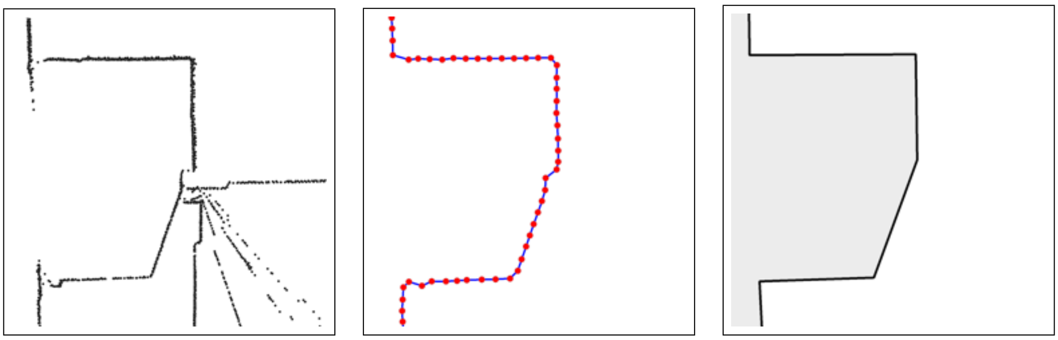
It has to be pointed out that the slicing of the point cloud was carried out considering a constant distance between slices Δ_h, to get a preliminary representation of the structure's geometry. A local reduction of Δ_h at the height of slabs, to be performed after the quality of the model is evaluated on the outcome of the first slicing attempt, could efficiently reduce the error recorded in these critical zones.

By inspecting Figure 13a, it can be noted that the constructed 3D model slightly intersects the point cloud. The non-intersection is a direct consequence of the method itself which constructs slide polygons from the intersections of planes with the point cloud and obtains the volume by the extrusion of the same polygons.

(a) Picture (b) North tower (c) North tower cloud detail

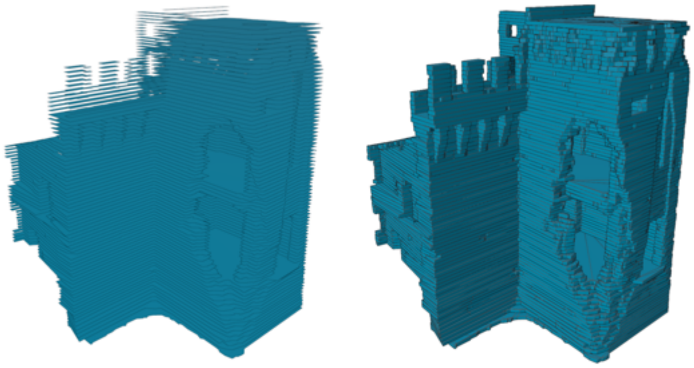


(d) Slice 1 (e) Slice 2 (f) Slice 3 (g) Slice 4 (h) Slice 5



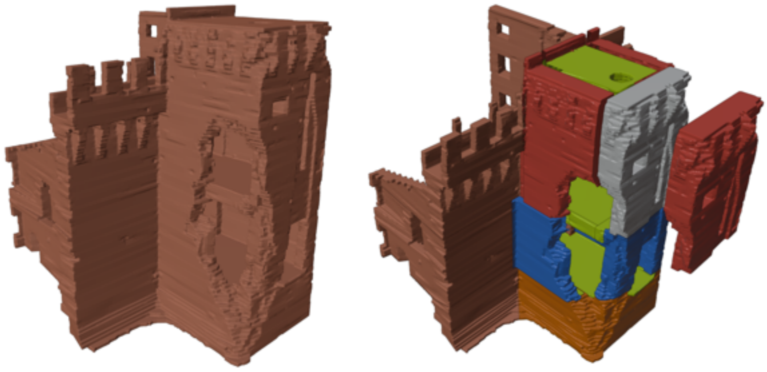
(i) Algorithm: **step 1** (j) Algorithm: **step 2** (k) Algorithm: **step 3**

Figure 10.: San Felice sul Panaro fortress. The areal view of the fortress (the north tower on the right) (a); North tower after the earthquake events (b); TIN mesh of the North Tower including some surrounding portions. Here red lines indicate the position of 5 representative plane sections (c) and points located at the 5 representative slices (d)-(h). The application of the Python-based Cloud2FEM procedure to this point cloud is illustrated over a magnification of a specific location (i)-(k).



(a) Geometry description through slices

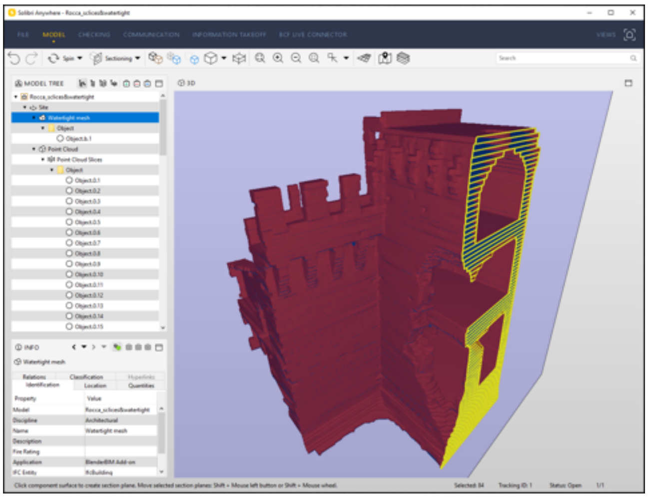
(b) Extruded slices



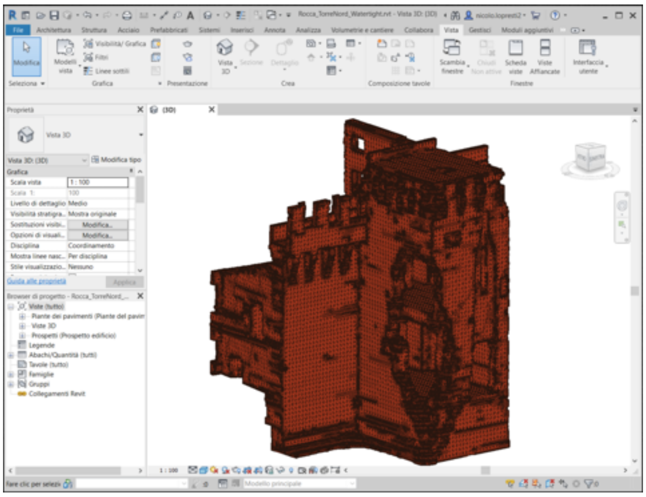
(c) Watertight boundary surfaces

(d) Watertight semantic portions

Figure 11.: Reconstruction of the architectural model: closed polygon slices (a); extruded slices (b); re-topology of boundaries surfaces (c); semantic partitioning of the geometry using watertight volumes (d).

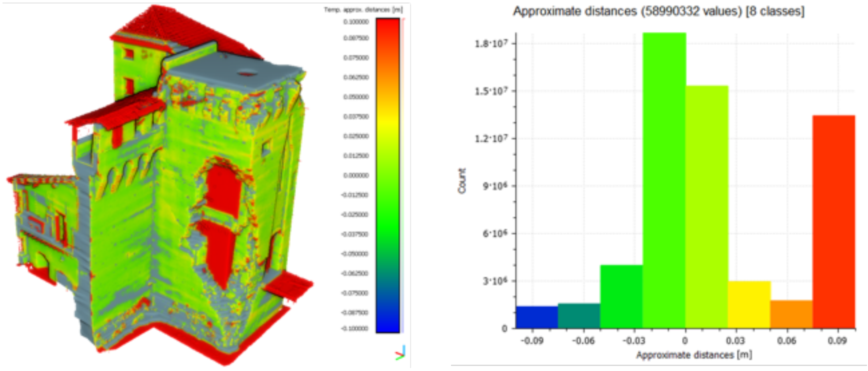


(a) Solibri



(b) Revit

Figure 12.: Integration of the model in BIM software



(a) Cloud Compare C2M

(b) Cloud Compare Histogram

Figure 13.: Geometric validation performed using Cloud-to-Mesh (C2M in Cloud Compare software).

5. Conclusions

This paper proposed a convenient workflow to obtain a simplified lightweight IFC description of point clouds of historic buildings, introducing a new transformation of point clouds into FE and architectural BIM models.

Particularly, the FE model generation has been found to guarantee the obtainment of a conforming solid FE mesh ready to be used in structural analysis. Analogously, the architectural BIM model generation has been achieved by slice extrusion to obtain the overall volume of the building. Accordingly, the assembly of independent slice-based meshes has been subjected to re-topology to obtain the overall watertight bounding surface of the building.

A pseudo-real historic structure has been adopted to test the effectiveness of the FE and BIM model generation procedures. Both showed a good efficiency and a high level of automation. Finally, the architectural BIM model generation of an actual historic structure has been carried out through the proposed workflow. A straightforward interoperability of the model between available commercial BIM software packages has been observed.

In conclusion, while the paper focuses on BIM modeling utilizing open-source tools like Blender, it is important to recognize the specific challenges and learning efforts associated with such tools. By acknowledging these considerations, we aim to contribute to a better understanding of the complexities involved in BIM modeling for historic buildings and the broader construction industry.

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