

# From TLS data into H-FEM model based on the quad-mesh: the case study of romanian church

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**Abstract** – Historical and architectural heritage assets are continuously exposed to a high risk of damage caused not only by natural events but also by poor maintenance or neglect. In order to preserve these structures, it is necessary to carry out a series of multi-level studies that provide a high level of support to all professionals working in this field. The use of appropriate geomatics techniques and instrumentation based on digital acquisition allow to build 3D models useful in several fields. The manuscript illustrates a methodology based on the use of quad-mesh able to obtain a 3D model for Heritage Finite Element Model (H-FEM); starting from the Terrestrial Laser Scanner - TLS survey of an architectural structure in a Romanian village, it was possible to import the 3D model in FEM software for structural analysis.

## I. INTRODUCTION

The point cloud generated by 3D digital survey technologies, such as Terrestrial Laser Scanner (TLS) and close range photogrammetry, allows to obtain the geometry of objects and/or structures investigated with great detail [1, 2]. Indeed, TLS is a tool capable of reconstructing 3D surfaces even from complex geometry and able to generate in a single scan millions of points in a few seconds with high accuracy. This means that when surveying large structures, it is necessary to carry out many scans with the generation of a dataset of even more than 100 M points. The modelling of complex architecture using parametric surfaces, useful for Building information Modeling - BIM (or Heritage BIM – HBIM, if it concerns cultural heritage structures) is quite complex. This process known as Scan-to-BIM process allows to assign to each surface or object specific parametric features and it is now rapidly penetrating the Architecture, Construction, Engineering and Facilities Management (AEC&FM) sectors [3-4]. Indeed, this process is useful in different

fields, such as restoration, requalification, facility management through a digital twin, Finite Element Model (FEM) analysis [5]. In general, this process includes six steps: (i) classification of considered elements, (ii) definition of required level of detail, (iii) scan data acquisition, (iv) point cloud registration and segmentation, (v) BIM creation and (vi) analysis [6]. Starting from the point cloud, one method for constructing surfaces is the triangular 3D mesh (Triangulated Irregular Network - TIN). The advantage of this surface is that it produces a surface with a simple structure that is precise to the original structure, since this surface passes through the points generated by the survey. However, the handling in common graphics software of these surfaces becomes complex if not impossible if the number of points is elevated. In addition, it is necessary to take into account that these surfaces do not always correspond to those to be parameterised. To overcome this situation, several methods have been developed.

Pepe et al., 2019 [7] discussed of the transformation of the point cloud generated point-cloud models of a stone bridges by photogrammetry technique and building a 3D model by non-uniform rational B-spline (NURBS) surface within Rhinoceros software (version 6, manufacturer: Robert McNeel & Assoc, Seattle, Washington, DC, USA) and special tools available in this software.

Wang et al. 2019 suggested three main future research directions within the scan-to-BIM framework: (i) the information requirements for different BIM applications should be identified, and the quantitative relationships between the modelling accuracy or point cloud quality and the reliability of as-is BIM for its intended use should be investigated; (ii) scan planning techniques should be further studied for cases in which an as-designed BIM does not exist and for unmanned aerial vehicle (UAV) mounted laser scanning; (iii) as-is BIM reconstruction techniques should be improved with regard to accuracy, applicability, and level of automation [8].

Costa-Jover et al. 2019 propose a simple and non-invasive methodology for evaluating masonry vaults from point clouds (generated by TLS), allowing relevant data on formal anomalies to be obtained [9]. The methodology has been tested on the vaults of the Gothic Cathedral of Tortosa; in this case, two-dimensional evaluation was performed by plotting the values reflected in the height histograms of each vault and by drawing the horizontal and vertical profile lines for comparison. The procedure developed by these authors can be applied easily to other vaulted constructions of any kind but is especially useful in dealing with the complex geometry of Gothic masonry vaults.

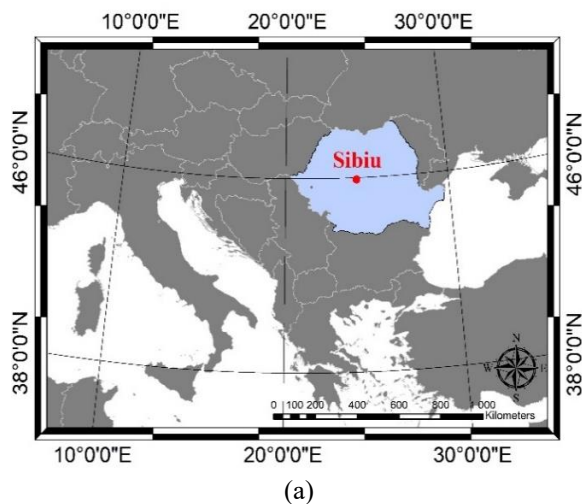
Qiu et al., 2022 proposed a method that can be summarized in two steps, first conducts a geometry-based segmentation to identify edge points and non-planar points, which contain critical geometric information and subsequently, a semantic-based segmentation is performed to identify points with critical semantic information [10].

Alfio et al., 2022 have developed a suitable methodology able to transform the TIN model of a big statue into a quad mesh model and finally into NURBS to be optimised and imported into a finite element calculation software [11].

Therefore, taking into consideration the papers just mentioned and especially the latest work based on the use of quad meshes, the paper aims to develop a scan-to-BIM methodology that can simplify the geometry of the structure as much as possible and, at the same time, guarantee high accuracy. In particular, the paper describes a methodological approach to build FEM model from point cloud. The structure taking into consideration concerns a church located in Sibiu (Romania).

## II. STUDY AREA

The structure under investigation is located in the village of Apoş, a town in Sibiu County, Transylvania, Romania (Figure 1a). The village, located on the Hârtibaciului plateau, has been inhabited since the Bronze Age, as confirmed by the numerous archaeological finds at the site.



(b)

Figure 1. Keymap (a) and Evangelical Church (b)

In particular, the architectural structure analysed in this manuscript is the Evangelical Church, built in the 15th century and included in the 2010 list of historical monuments in Romania (Figure 1b).

The Gothic-style church, consisting of a single nave and a polygonal apsidal choir supported by buttresses, was transformed in the 18th century. Later, a bell tower was built in 1799, isolated from the structure and located 6.50 m west of the church.

## III. METHOD

To build a parametric model, an appropriate methodology was developed to make the process simple and accurate. Through the Scan-to-BIM process, it was possible to realise the reverse engineering that starting from a point cloud and 3D meshes makes it possible to obtain a parametric model.

The conversion from point cloud to BIM object can be realized using several steps: i) 3D survey by TLS and generation dense point cloud; ii) conversion the point cloud into mesh model; iii) transformation in quad mesh a subsequently reduction of quad mesh; iv) identification of level of reduction; v) import and management in FEM environment.

### A. TLS data Collection

The TLS used for the survey of the church was the Z+F IMAGER® 5010C manufactured by Zoller and Fröhlich GmbH, Wangen, Baden-Württemberg, Germany. The 5010C (Figure 2) is a phased system using a class 1 infrared laser and has an exceptionally high and fast data acquisition rate of 1.06 million points per second while maintaining a linearity error of less than 1 mm, within 20 m of the surface [12].

22 scans were carried out in order to cover the church. The post-processing of TLS data was carried out using Z+F LaserControl software (rel. 9 Office version); the scans were aligned manually using as reference points the flat targets that had been accurately positioned inside the investigated site.



PARAMETER	VALUE
Radius divergence	<0.3 mrad
Range	187.3 m (unambiguous range)
Min. distance	0.3 m
Resolution range	0.1 mm
Acquisition capacity Max.	1,016,000 pixels/sec.
Linear error	<1 mm
Vertical/horizontal field angle	320° / 360°
Vertical/horizontal resolution	0.0004° / 0.0002°
Vertical/horizontal accuracy	0.007° rms / 0.007° rms
Max. rotational speed	50rps (3,000 rpm)

Figure 2. Screen of Z+F features

A visualisation of the point cloud of the surveyed area generated by TLS process is shown in Figure 3; in particular, a total amount about of 44 M of point was generated. The point cloud generated by the TLS needs to be cleaned since there are elements outside the structures to be surveyed in the scans, such as vegetation, external pipes, power lines, etc. For this reason, in Autodesk Recap Pro the removal of points external to the scan to be investigated was carried out. In fact, the new point cloud consists of 10 million points.



(a)



(b)

Figure 3. Point cloud generated by the TLS survey: outside (a) and inside scan acquisition (b).

### B. From point cloud to polygonal mesh

Reconstructing surfaces from point cloud presents a number of difficulties in practice. Sampling of points is often non-uniform, and positions and normals are noisy due to inaccurate sampling and poor scan registration. In addition, accessibility constraints during scanning can leave some regions of the surface without data.

Faced with these challenges, reconstruction methods attempt to infer the topology of the surface. Over the years, several methods have been developed, such as Delaunay triangulations [13], Voronoi diagrams [14] and Global fitting [15]. Kazhdan et al. 2006 transformed the computation of the indicator function into a standard Poisson problem [16]. This mean finding the scalar function  $\chi$  whose gradient best approximates a vector field  $\vec{V}$  defined by the samples:

$$\min_{\chi} \|\nabla\chi - \vec{V}\| \quad (1)$$

Indeed, applied the divergence operator to transform this computation of the indicator function into a standard Poisson problem, which is to compute the scalar function  $\chi$  whose Laplacian equals the divergence of the vector field:

$$\Delta\chi \equiv \nabla \cdot \nabla\chi = \nabla \cdot \vec{V} \quad (2)$$

Kazhdan and Hoppe (2013) extended the Poisson surface reconstruction technique, incorporating sample weight values assigned for interpolation of missing points [17].

Triangular meshes generated from dense point clouds are very several; this mean that is necessary to reduce the number of the meshes in order to obtain an easily manageable model for subsequent BIM analysis. In the simplification of triangular meshes, the main challenge is to obtain a mesh with a reduced number of faces that approximates the input shape well. However, the simplified 3D mesh model may not be suitable for our purposes. In fact, as shown in Alfio et al. (2022), the use of quad mesh surfaces could be a valid tool for 3D modelling in order to obtain parametric surfaces and objects [11].

The creation of polygonal meshes is based on the idea of cell decomposition where triangles and quadrilaterals are the most common shapes of cells in this decomposition. Quadrilateral meshes, which are composed of quadrilaterals, have been widely used in computer graphics because some geometric tasks are better solved using quadrilateral meshes than triangle meshes [18].

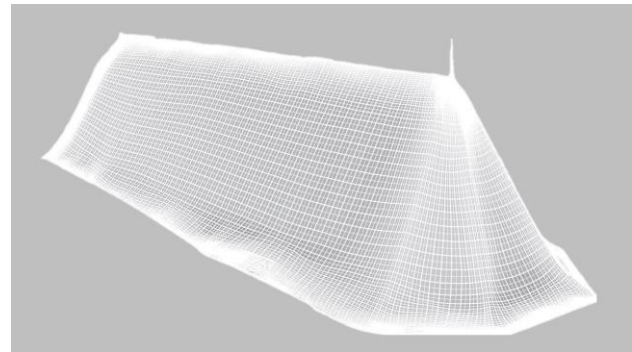
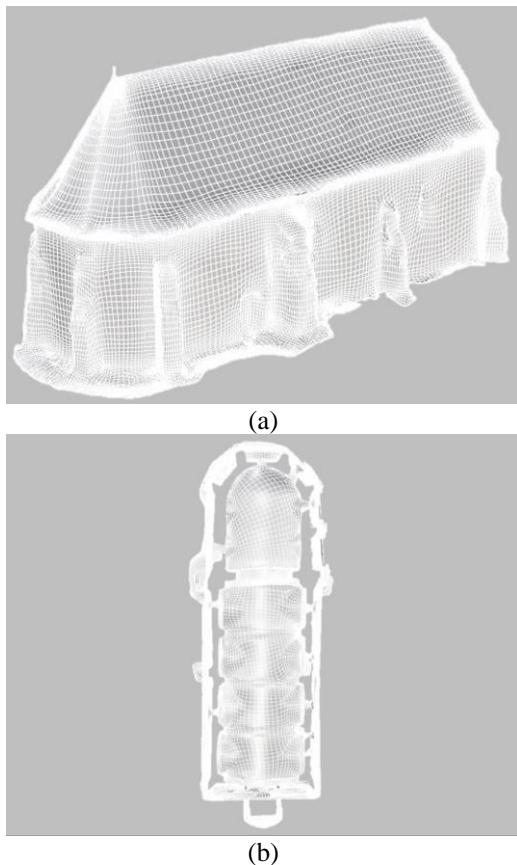
The constituents of a two-dimensional polygonal mesh are facets, edges that bound facets, and vertices that bound edges. In a conforming mesh, any two faces share either a single vertex, or an entire common edge. A particular type of mesh is called T meshes, where two faces may share only a part of an edge. In 3D modelling using meshes surfaces, in general the meshes are manifold, i.e., any edge may be shared by either one or two incident facets and the

set of facets connected to each vertex forms a single fan, that mean there is no “bow tie” configuration [19].

The main challenge in the simplification of quad meshes is to obtain a mesh that maximises regularity in terms of both connectivity (valence of vertices) and geometry (shape of vertices), vertices and geometry (shape of elements), while the quality of approximation is usually only addressed as a secondary issue. Therefore, the tri-to-quad conversion method combines a sequence of local operations on connectivity to convert triangular meshes into quad meshes. One main mechanism is to fuse two original triangles into one quad; so basically, the tri-mesh to quad-mesh conversion is based on pairing original adjacent triangles. This class of methods can only be expected to produce unstructured quad meshes, not regular ones. To obtain a pure quad-meshes in this way, the original mesh must have an even number of triangles. This is always the case for closed meshes; otherwise, it can be trivially enforced by splitting one border triangle in two [20]. For a better handling of the polygonal mesh model, it was necessary to carry out a pre-processing of the data, applying algorithms to simplify and reduce the number of faces.

#### IV. RESULTS AND DISCUSSION

The results of the optimisation and simplification process of the quad-mesh model, generated in the Rhinoceros environment, are illustrated in Figure 4.



(c)

Figure 4. Quad-mesh models: axonometric view (a), horizontal section (b), general view of the roof (c).

The structural elements that make up the church were analysed separately, in order to attribute physical and mechanical properties to each of them.

In this way, it was possible to generate a model suitable for FEM analysis. In particular, the roof model was imported, managed and processed in the Midas FEA NX environment. (Figure 5).

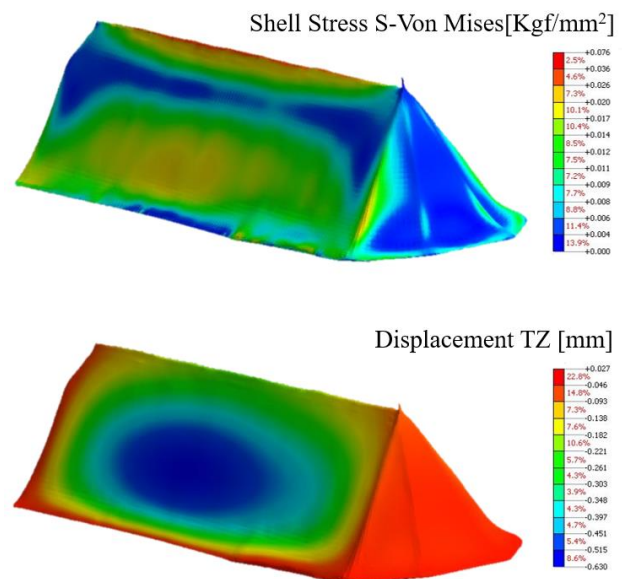


Figure 5. FEM modelling in Midas software of the roof.

The import of the quad mesh allowed for easy and rapid processing in the FEM environment. An approach involving the import of the TIN model was also experimented with; the TIN model, although reduced in number, presented considerable problems such as the management of individual meshes (open and/or extremely short edges, faces in which the normal to the face differs significantly from the normals to the vertices, non-manifold faces, etc.), as well as problems related to excessive import and processing times in FEM software.

## V. CONCLUSIONS

In the experimentation, a methodological approach was described in order to create a detailed and accurate 3D model from a point cloud using TLS instrumentation. In this case study, a 3D model of the Evangelical Church belonging to the Cultural Heritage and included in the list of Romanian historical monuments was built. This model, suitably elaborated by means of simplification algorithms and reduction of the number of faces, and by means of transformation algorithms from a TIN model to a polygonal mesh model (quad-mesh) was imported into the FEM environment for a numerical finite element analysis.

This approach made it possible to obtain, in a short time and with reduced computational capacity, an easy-to-use H-FEM model for subsequent structural condition analyses.

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