ACTA IMEKO
ISSN: 2221-870X
June 2024, Volume 13, Number 2, 1 - 8

Quad-mesh modelling for finite element method applications in heritage structures

Vincenzo Saverio Alfio[1], Domenica Costantino[1], Massimiliano Pepe[2], Sorin Herban[3], Alfredo Restuccia Garofalo[1]

[1] *Polytechnic of Bari, DICATECh, via E. Orabona 4, 70125 Bari, Italy*
[2] *University of Chieti-Pescara"G. d'Annunzio", Department of Engineering and Geology (InGeo), 65127, Pescara, Italy*
[3] *Poliltehnic University of Timisoara, Traian Lalescu 2°, 300223, Timisoara, Romania*

ABSTRACT
The historical architectural heritage is often exposed to a high risk of damage due not only to natural events, but also to poor maintenance or neglect. In order to preserve it, it is necessary to conduct a series of multilevel and multidisciplinary studies capable of supporting the design choices for all the figures working in this field. The use of appropriate geomatic techniques and the choice of suitable sensors based on digital acquisition, allow the elaboration of accurate, high-performance 3D models with high quality photorealistic content. In this manuscript, a methodology is illustrated that, starting from the generation of a point cloud (TLS survey or integration of different digital sensors) allows the elaboration of an accurate 3D model for two different case studies from the point of view of architecture and survey data acquisition. In order to analyse these architectures from a structural point of view, the 3D model is optimised and transformed from a TIN model into a polygonal model (Quad-Mesh). This process represents a new approach in the management of complex architectures, capable of responding optimally to the computational capabilities for FEM (Finite Element Model) analysis, for the structural characterisation of the elements under investigation.

Section: RESEARCH PAPER

Keywords: Quad-mesh; 3D model; photogrammetry; TLS, 3D survey; scan to FEM

Citation: V. S. Alfio, D. Costantino, M. Pepe, S. Herban, A. Restuccia Garofalo, Quad-mesh modelling for finite element method applications in heritage structures, Acta IMEKO, vol. 13 (2024) no. 2, pp. 1-8. DOI: 10.21014/actaimeko.v13i2.1809

Section Editor: Fabio Leccese, Università Degli Studi Roma Tre, Rome, Italy

Received February 27, 2024; **In final form** March 21, 2024; **Published** June 2024

Corresponding author: Vincenzo Saverio Alfio, e-mail: vincenzosaverio.alfio@poliba.it

1. INTRODUCTION

The process of transforming the point cloud into a parametric 3D model is an important research activity, especially when dealing with complex surfaces. Indeed, especially in the field of cultural heritage, where the structures to be 3D modelled involve buildings or structures with complex geometry. The process that enables the transformation from point cloud into parametric objects is called scan-to-BIM [1], [2]. This means, in the field of structural modelling to a process called "scan-to-FEM". Actually, it is customary to define the transformation process involving historic buildings as scan-to-heritage BIM (or even HBIM) [3]-[5]. In fact, in the case of historic buildings with complex geometry, it is necessary to generate a very large dense point cloud to define the 3D geometry [6]. Consequently, the identification of strategies for the creation of parametric models assumes an important role for a correct, accurate and efficient management of the meshes generated from the point cloud. Over the years, several methods have been developed for generating parametric models.

Adami et al. 2017 [7] presented an approach to address the challenge of representing intricate heritage structures using parametric elements; to account for any modelling errors, the authors suggest overlaying the parametric model with a false-colour map, which visually illustrates the disparity between the model and the actual representation of the heritage site as captured by the point cloud data. Wang et al., 2019 [8] proposed three key areas for future research in the scan-to-BIM framework. Firstly, they suggested the need to identify the information requirements for different BIM applications and explore the quantitative relationships between the accuracy of modelling or point cloud quality and the reliability of as-is BIM for its intended use. Secondly, they emphasized the importance of further studying scan planning techniques, particularly in cases where an as-designed BIM is not available and for unmanned aerial vehicle (UAV) mounted laser scanning. Lastly, they highlighted the need for improvements in as-is BIM reconstruction techniques, focusing on enhancing accuracy, applicability, and level of automation. Martínez-Carricondo et al. 2020 [9] have developed a model of a heritage building complex in Spain using solely UAV photogrammetry data. Their aim is to emphasize the significance of integrating both nadir and oblique photographs to eliminate any potential gaps in the model. To achieve this, they have utilized BIM software to directly create a library of parametric objects. These objects are generated based on the point clouds and meshes imported into the software through plugins.

Recently, the development of some modelling software capable of generating parametric objects has generated a new method for generating the reverse engineering process. Furno et al., 2017 [10] conducted a comparison between two different modelling methods, one based on the use of NURBS while the other was based on BIM objects in Rhinoceros and Autodesk Revit; indeed, Rhinoceros, with its "direct" modelling capability, allowed for the processing of survey data and the creation of a model divided into blocks. Subsequently, Pepe et al., 2019 [11] examined the process of converting point cloud data obtained by photogrammetry into point cloud models of stone bridges; this latter method is based on the use of Rhinoceros software (version 6, manufacturer: Robert McNeel & Assoc, Seattle, Washington, DC, USA) and its specialized tools to build a 3D model using non-uniform rational B-spline surfaces (NURBS). In this line of research, Alfio et al., 2022 [12] wrote an effective approach to convert the Triangulated Irregular Network (TIN) model of a large statue into a quad mesh model; subsequently, this quad mesh model can be transformed into NURBS, which can then be optimized and imported into a finite element calculation software.

Therefore, this paper aims to continue using the Rhinoceros-Grasshopper environment for quad-mesh generation and efficient parameterization of objects to be imported into the FEM environment. The paper outlines a systematic approach to constructing a Finite Element Method (FEM) model using a point cloud. This approach specifically focuses on a church situated in Sibiu, Romania, as well as an underpass located in a significant archaeological area in Italy.

2. MATERIALS AND METHODS

2.1. Cases studies

For the application of the proposed methodology, two different case studies were identified (Figure 1a). Specifically, the first case study concerns the roof of an evangelical church built in the 15th century and included in the 2010 list of Romanian historical monuments. This architectural structure, in Gothic style and composed of a single nave, is in the village of Apoş, a town in the county of Sibiu, Transylvania, Romania, and was built in the 10th century. Later, in the 18th century, the church was transformed until 1799, when the bell tower was built, isolated from the structure, and located 6.50 m west of the church (Figure 1b).

The second case study analysed concerns an ancient subway that serves as a connection between two archaeological areas, consisting of a structure predominantly made of masonry, currently located underneath a major provincial road. The area of interest is in the countryside of Oria, Brindisi (Italy) and is part of a rock complex consisting of a Messapian quarry from 700 BC, a Roman cart road from 100 BC and a Basilian crypt from the 5th century AD. Recently, following conservative restoration work to restore the integrity of the original body, all the aforementioned architectural elements have emerged. The old masonry subway crosses the existing road platform; this subway has cracks and subsidence that affect the superstructure, consequently causing problems to the existing road system (Figure 1c).

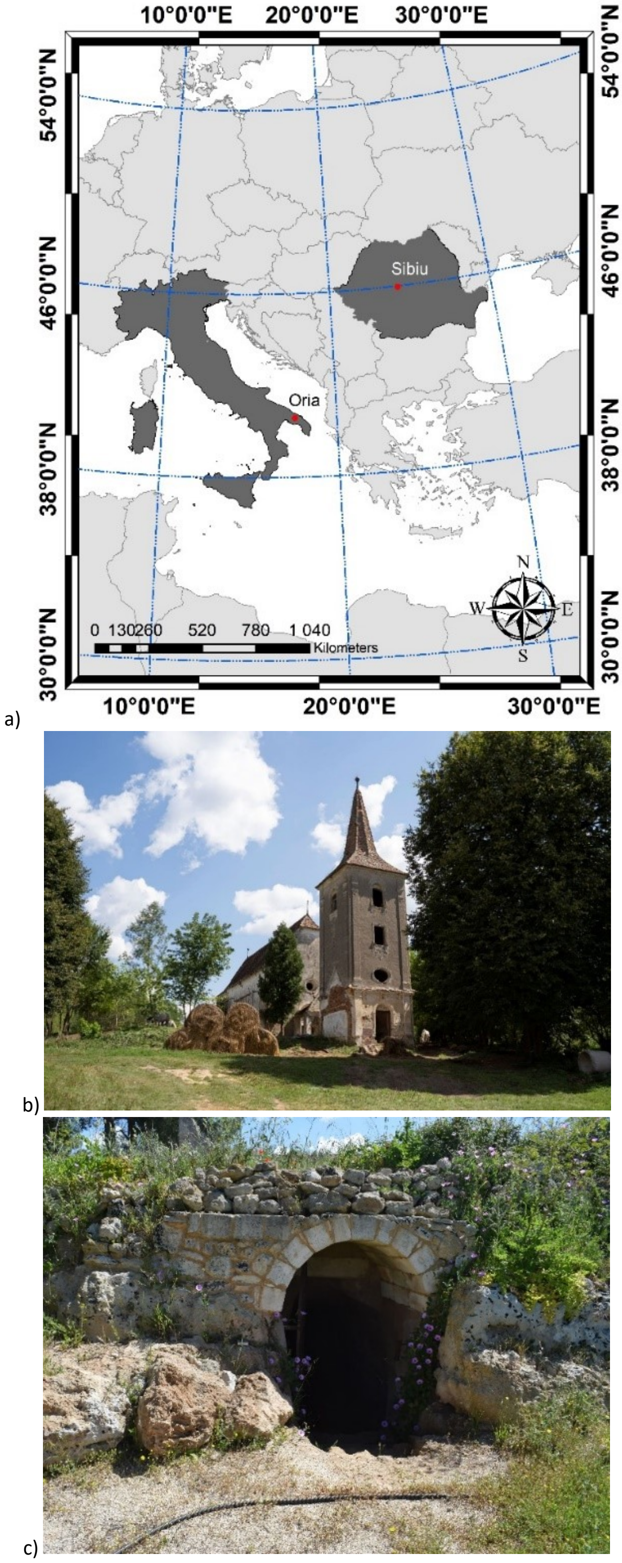


Figure 1. a) Geolocalization of the studies areas; b) Romanian church and c) entrance to the ancient subway connecting the archaeological sites.

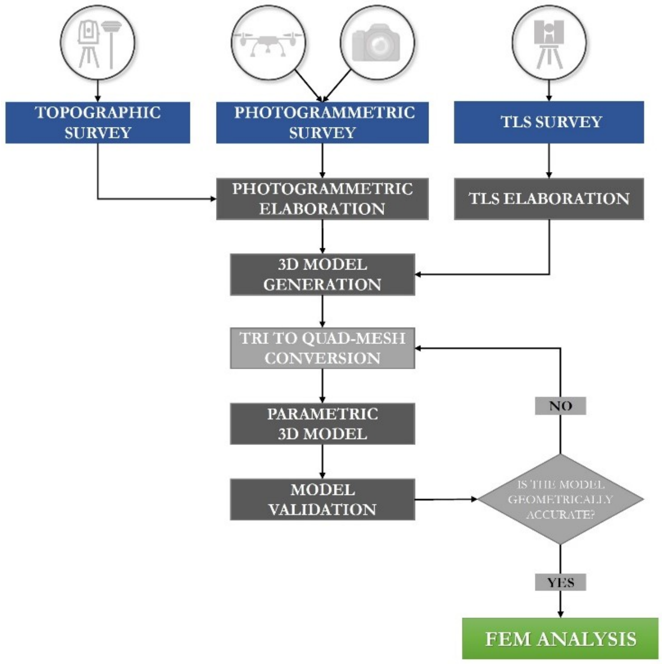


Figure 2. Pipeline of the proposed methodological approach.

2.2. Methodological Approach

The methodological approach proposed in this manuscript makes it possible to obtain an optimised, high-performance three-dimensional model for subsequent static analyses.

Starting from a geomatic survey and through the use of appropriate sensors and techniques, the aim is to obtain a 3D model characterised by triangular mesh surfaces, or TINs (Triangulated Irregular Network), which through appropriate tools and algorithms are transformed into polygonal meshes or described by Quad-Mesh. This model, decimated and simplified according to the required accuracy, is subsequently parameterised and validated before being imported into FEM solvers for subsequent analysis.

The main steps of the process, starting with the survey and using suitable active and/or passive sensors, is summarised by the pipeline shown in Figure 2.

2.2.1. Survey and elaboration of the 3D model

For the elaboration of an accurate 3D model, the planning and conducting phase of the survey is important. In fact, depending on the geometry and complexity of the area to be surveyed, it is necessary to adopt the best survey techniques and, where necessary, integrate different data acquisition techniques in order to obtain a high-performance dataset.

For the realisation of 3D models, both photogrammetric and TLS (Terrestrial Laser Scanner) techniques can be used; however, the characteristics and qualities of the final output must be taken into consideration. In the study areas analysed, both CRP (Close Range Photogrammetry) and TLS techniques were used, depending on the complexity and geometry to be acquired. In particular, for the survey of the roof of the church, a phase-measured TLS was used, while for the survey of the underground subway, terrestrial and UAV photogrammetry techniques were integrated. For the scaling and georeferencing of the model, a survey with TS (Total Station) and GNSS (Global Navigation Satellite System) was conducted.

TLS technology makes it possible to obtain a high-precision, high-quality end product in a short time, while close-range photogrammetry techniques make it possible to obtain accurate 3D models with high geometric resolution and a high photorealistic content. Furthermore, where the area to be surveyed is difficult to reach or inaccessible, UAV photogrammetry becomes a necessary acquisition tool.

For this reason, a subsequent integration phase between the different datasets should be considered in the planning phase in order to obtain a high-performance model.

In both cases, the resulting model is represented by a dense, coloured point cloud capable of accurately reconstructing the surveyed geometries.

From the point cloud, a triangular mesh surface model, i.e. a TIN (Triangulated Irregular Network) model, can be generated using appropriate tools.

Reconstructing surfaces from point clouds presents several difficulties, such as sampling the points, determining positions and normals, which can produce regions of the surface without data. Various methods have been developed over the years, such as Delaunay triangulations [13], Voronoi diagrams [14], global fitting [15] or the method proposed by Kazhdan et al. 2006 who transformed the calculation of the indicator function into a standard Poisson problem [16], finding the scalar function χ whose gradient best approximates a vector field $V^{\rightarrow}$ defined by the samples:

$$\min_{\chi} \left\| \nabla_{\chi} - \vec{V} \right\|, \tag{1}$$

By applying the divergence operator, it is possible to transform the calculation of the indicator function into a standard Poisson problem, which consists of calculating the scalar function χ whose laplacian is equal to the divergence of the vector field:

$$\Delta\chi \equiv \nabla - \nabla\chi = \nabla - \vec{\nabla}_{\chi}, \tag{2}$$

Although these simplify the storage of data and reduce the number of algorithms required for its processing, they could generate various problems in the storage and management of models, affect the processing in terms of computational resources and hardware memory usage, and generate topological and surface geometry errors.

For these reasons, it is necessary to convert the TIN model, by applying a series of simplification and decimation algorithms and tools, into a mesh model composed of quadrilateral elements.

2.2.2. TIN to Quad-Mesh model and NURBS conversion

To convert meshes from triangular to polygonal, it is necessary to apply a series of simplification algorithms capable of reconstructing meshes composed of quadrilateral elements.

Recently, the automatic generation of polygonal meshes (remeshing) through the implementation of dedicated algorithms has been integrated into commercial software, such as Rhinoceros.

These algorithms perform complex calculations on the input mesh, studying the geometries of the objects and analysing the points of curvature. This also makes it possible to control the number, size, orientation and alignment of the quadrilaterals, and to preserve the characteristics of the original geometry.

Based on the results obtained, these algorithms generate and position quadrangles (Figure 3).

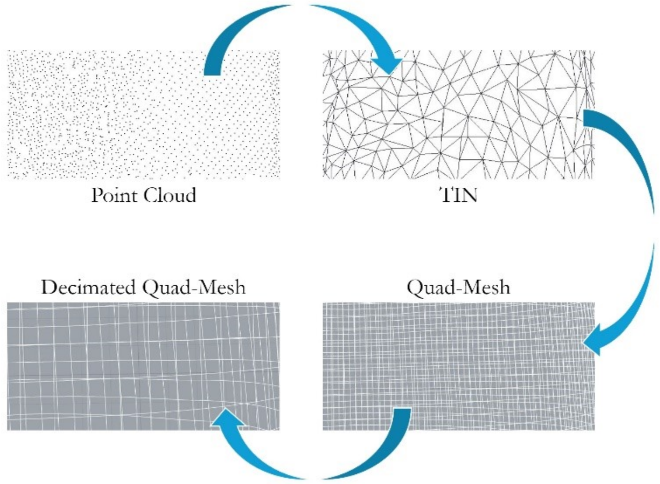


Figure 3. Transformation of the point cloud into a quadrangular polygonal model via a TIN surface.

The quad-mesh model generated in this way, however, is dense with polygons and does not lend itself well to subsequent analysis; for this reason, it is necessary to carry out a kind of simplification and decimation of the generated model, paying particular attention to the desired level of accuracy of the final output.

Therefore, at this stage it is important to determine the remeshing mode, i.e. whether to define the approximate edge length of the output mesh or the approximate number of faces of the output mesh as the target of the algorithm. In the first case, the resulting number of faces increases with the scale of the object, while in the second case, a minimum number of quadrangles and uniform dimensions can be set, in which the size of the quadrangles can be reduced according to the higher curvature areas.

The generated quad-mesh model is transformed into a NURBS (Non Uniform Rational Basis Splines) geometry that expresses the mathematical representation of 3D geometry, capable of precisely defining any shape. In fact, such geometries are extremely flexible and suitable for all modelling processes. In general, NURBS follow the theory of Bezier curve models generated through the following mathematical formulation [17]:

$$C(u) = \sum_{i=1}^{n} \frac{N_{i,n}(u) \cdot w_i}{\sum_{j=1}^{k} N_{j,n} \cdot w_j} \, P_i \, , \tag{3}$$

where:

w_i weights;

P_i control points;

$N_{i,n}$ are the normalised B-Spline basis function of n degree.

$$N_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \leq u \leq u_{i+1} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\begin{aligned} N_{i,n}(u) = {} & \frac{u - u_i}{u_{i+n} - u_i} N_{i,n-1}(u) \\ & + \frac{u_{i+n+1} - u}{u_{i+n+1} - u_{i+1}} N_{i+1,n-1}(u) \, , \end{aligned} \tag{5}$$

where u_i are the knots forming the knot vector:

$$U = \{ u_0;\, u_1; \ldots;\, u_{n+n+1} \} \, . \tag{6}$$

In addition to describing curves, NURBS can also be extended to the two-dimensional case to describe surfaces [18].

In this case we speak of control vertices, surface patches, grade and parameters u, v. Since these are two-dimensional surfaces, the coordinates of the points belonging to them are determined by two independent parameters called u, v.

$$S(u,v) = \sum_{i=1}^{k} \sum_{j=1}^{l} R_{i,j}(u,v) \cdot P_{i,j} \, , \tag{7}$$

where the rational basis function holds:

$$R_{i,j}(u,v) = \frac{N_{i,n}(u) N_{j,m}(v) w_{i,j}}{\sum_{p=1}^{k} \sum_{q=1}^{l} N_{p,n}(u) N_{q,m}(v) w_{p,q}} \, . \tag{8}$$

Surface patches are equivalent to EPs (End Points) for a NURBS surface. The number of surface patches nSP is related to the number of CVs (Control Vertex) in a similar way to EPs:

$$nSP_u \cdot nSP_v = (nCV_u - degree) \cdot (nCV_v - degree) \, . \tag{9}$$

All NURBS surfaces derive from a spatial deformation of a grid of square SP surfaces side-by-side and, the node images ($i =$ 1, …, n) divide the curve into segments that play the role of finite elements in an analysis context.

2.2.3. Implementation in FEM software

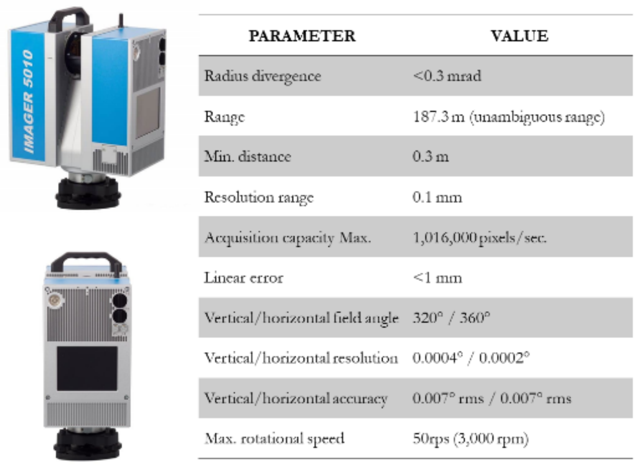
For the implementation of the polygonal model in the FEM environment, it is necessary to transform NURBS surfaces into solids. The generation of the solid model takes place through Boolean operations in which it is necessary to introduce the thicknesses of the structural elements, their material composition and the connection characteristics of the various portions of the structure.

The latter were identified and recorded during the survey activities and during the subsequent data processing phases.

Starting from the polygonal model, it is then possible to transform the NURBS-type geometry into a structured mesh, making it possible to differentiate the various elements of the structure by assigning each of them a specific material and its physical-mechanical properties. To characterise the structural behaviour of the investigated sites, load conditions were defined and basic and lateral constraints were set in order to conduct a FEM analysis using Midas FEA NX software (MIDASoft, Inc., New York, NY). The choice of this software is based on the fact that it has advanced modelling tools and instruments and that, thanks to its compatibility with other formats, it can achieve high performance in a short time. In addition, the possibility of managing numerous meshes allows the finite element model to be represented and solved more accurately reproducing the solid geometry previously created.

2.3. Quad-Mesh modelling applied on the church roof

In this case study, the modelling of the church roof was considered, using geomatic data acquired using TLS. For the survey of the entire structure, the TLS Z+F IMAGER® 5010C manufactured by Zoller and Fröhlich GmbH, Wangen, Baden-Wurttemberg, Germany, was used (Figure 4). This TLS is a phased-array system using a class 1 infrared laser and has an exceptionally high and fast data acquisition rate of 1.06 million points per second, maintaining a linearity error of less than 1 mm, within 20 m of the surface [19].



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 4. Main features of the TLS used in the experimentation.

In order to survey the entire church, 22 scans were acquired. The post-processing of the data was performed using the Z+F LaserControl software (Rel. 9 Office version) [20].

In this way, it was possible to obtain a dense point cloud of approximately 44 million points; subsequently, 3D point cloud was filtered and cleaned, also removing any outliers in order to eliminate elements external to the investigated scene such as vegetation, external pipelines, power lines, etc.

The result of this phase is a new point cloud consisting of 10 million points (Figure 5).

From the point cloud, processing was carried out in order to obtain a triangular mesh surface model, which, however, had a large number of triangles and was therefore very complex to be analysed by FEM software.

Figure 5. 3D point cloud of the church.

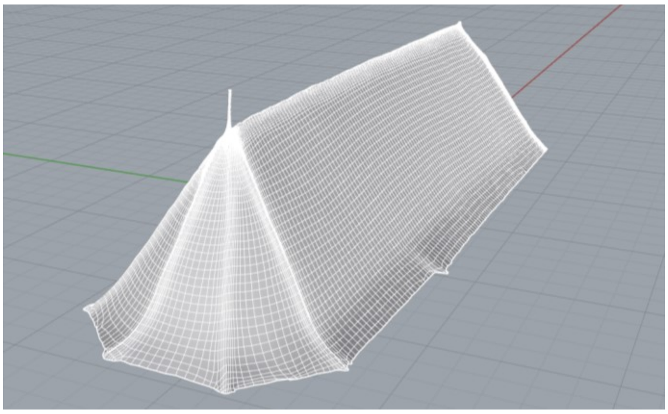


Figure 6. Quad Mesh model of the church roof.

To overcome this difficulty, the model was imported into Rhinoceros software where, using appropriate tools and algorithms, the mesh was decimated. In the case study analysed, the mesh was decimated by 90 per cent, while still guaranteeing a high degree of detail and accuracy with respect to the point cloud. Furthermore, the mesh thus generated was analysed from a geometric point of view. In particular, the presence of self-intersections, interpenetrating meshes and non-manifold surfaces, i.e. mesh edges that have more than two faces connected to a single edge, were checked.

In order to generate a continuous mesh for subsequent finite element modelling, at this stage, the self-intersecting faces were then manually corrected and deleted, creating a hole in the geometric mesh, which was subsequently regularised using smoothing functions.

After this step, it was possible to transform the triangular mesh into a quad-mesh by redefining the entire topological structure of the model, consistent with that generated by the point cloud (Figure 6). The quad-mesh was then converted into a NURBS geometry, thereby optimising the subsequent step of importing the model into the FEM environment.

2.4. Quad-mesh modelling applied for the ancient subway

The survey of the hypogeal subway was performed by means of UAV - Unmanned Aerial Vehicle photogrammetry and terrestrial photogrammetry. In particular, for the acquisition of nadiral images, a survey was carried out using a DJI drone mod. Mavic 2 PRO equipped with a 20 MP camera and a 1" CMOS sensor; for the acquisition of the internal scenes, a terrestrial photogrammetric survey was carried out using a Nikon D3300 model DSLR camera with a 24 MP resolution equipped with an 18 mm fixed focal length lens.

The entire survey resulted in the acquisition of 449 UAV images for the reconstruction of the road and the archaeological area, while 994 images were acquired using the CRP technique for the interior of the subway.

The two different datasets were processed using the Agisoft Metashape photogrammetric software in order to construct a dense coloured point cloud consisting of approximately 30 million points (Figure 7).

The 3D model was georeferenced in a local reference system through the acquisition of 22 GCPs (Ground Control Points) surveyed using Total Station. The Total Error (mean square deviation) obtained from the referencing process was 0.01 m. Furthermore, in order to contextualise the survey in the existing thematic cartographies, a GNSS (Global Navigation System

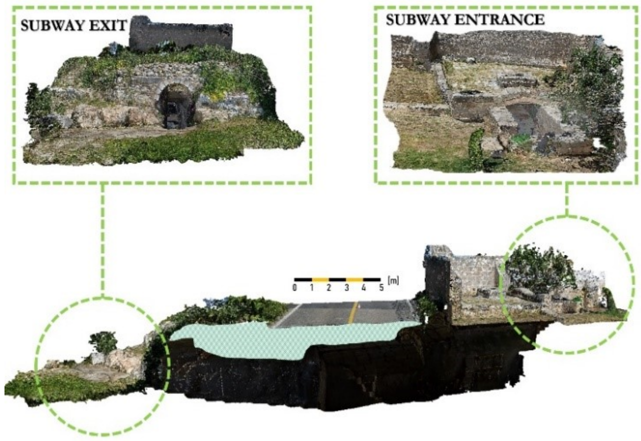


Figure 7. 3D views of the site using point cloud.

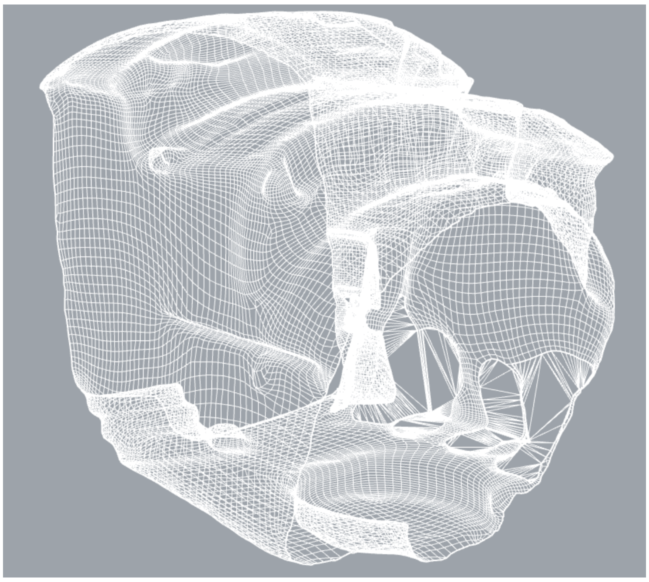


Figure 8. Quad-mesh reconstruction of the investigated structure.

Satellite) survey was carried out in the UTM33N - ETRF2000 reference system.

Using the Agisoft Metashape photogrammetric software, it was also possible to generate the 3D model with numerous triangular mesh. The handling of the latter model within an FEM solver is rather complex; this becomes particularly important when the geometry of the structure or object is articulated. For these reasons, as described for the previous case study, it was necessary to optimise the surfaces through a reduction in the number of faces that make up the network. In particular, a reduction of approximately 80% of the overall geometry was carried out. Subsequently, the model was analysed in order to eliminate all possible topological and geometrical errors and was converted into a quad-mesh model. Taking into account the complexity of the subway geometry, the quad-mesh represents a valid solution for modelling this type of complex structure (Figure 8).

In this way, it is possible to obtain an accurate modelling of each component of the surveyed object and to avoid the problem of working with a mesh that is not properly structured and difficult to handle, both for modelling and for the computational aspects related to the subsequent FEM analysis.

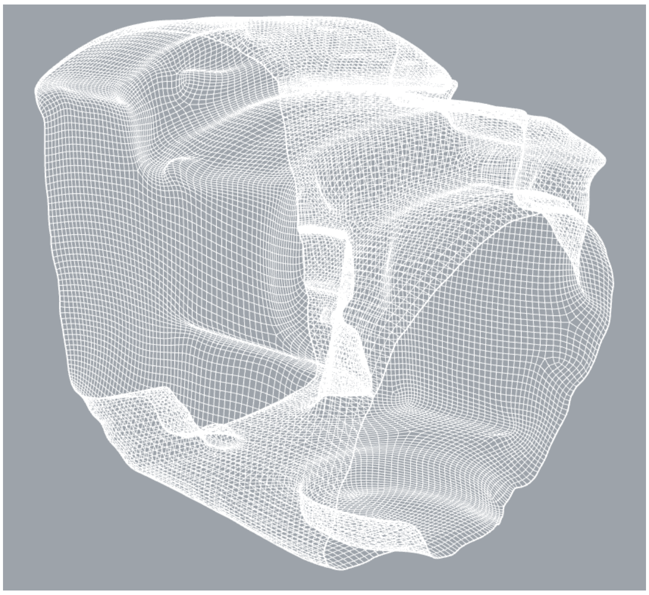


Figure 9. Removal of external elements and reconstruction of the quad-mesh model.

Furthermore, in order to improve the quality of the final result and the reliability of the subsequent analysis results, it was necessary to eliminate all non-structural elements and objects, such as amphorae positioned along the perimeter walls of the subway would not have allowed a correct import of the model into the FEM environment. For this reason, it was necessary to eliminate them from the 3D model by creating a series of holes directly on the surfaces of the quad-mesh; subsequently, through Boolean commands and mesh transformations, it was possible to remodel the missing parts and thus generate a model composed of more regular quad-mesh (Figure 9).

3. RESULTS

The two-dimensional geometric meshes were converted into NURBS polysurfaces and saved in the ACIS and Parasolid export formats. The former is a translator allowing data exchange between systems based on the kernel of the same name [21]; the latter is a geometric kernel originally developed by Shape Data Limited and now owned by the Siemens PLM Software group [22]. In general, the choice of the most appropriate file export format must take into account not only the characteristics and information exported, but also the size of the resulting file. In fact, files with a large size are often not manageable by all programmes, as they require high computational capacities and, consequently, do not meet the requirements of optimal model management. Using these formats, the geometries were imported into the FEM software Midas NFX in order to validate and analyse the models.

In particular, the different parts of the models had to be identified and subdivided according to material type and then, through a 3D meshing phase, the properties and all mechanical-reactive characteristics could be assigned. Based on the size of the analysed objects, it was decided to set the 3D meshing with a mesh step of 0.50 metres.

Once the model with the different characteristics was generated, the constraining reactions and their stresses were assigned, and finally the structure's own weight was imposed.

Finally, it was possible to launch the analyses, performing a linear static analysis on the models produced and visualising the results obtained in terms of stresses and deformations in the case of both the roof (Figure 10) and the ancient subway (Figure 11).

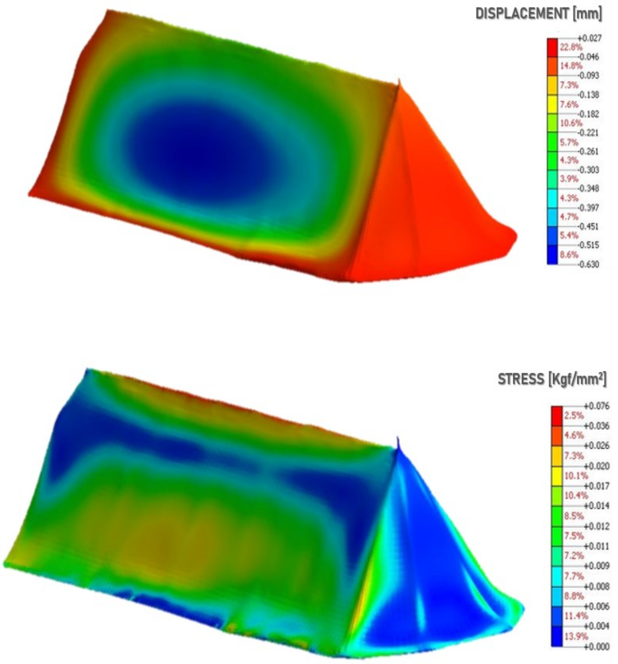


Figure 10. Results in terms of displacements and stress obtained from the FEM analysis of the roof.

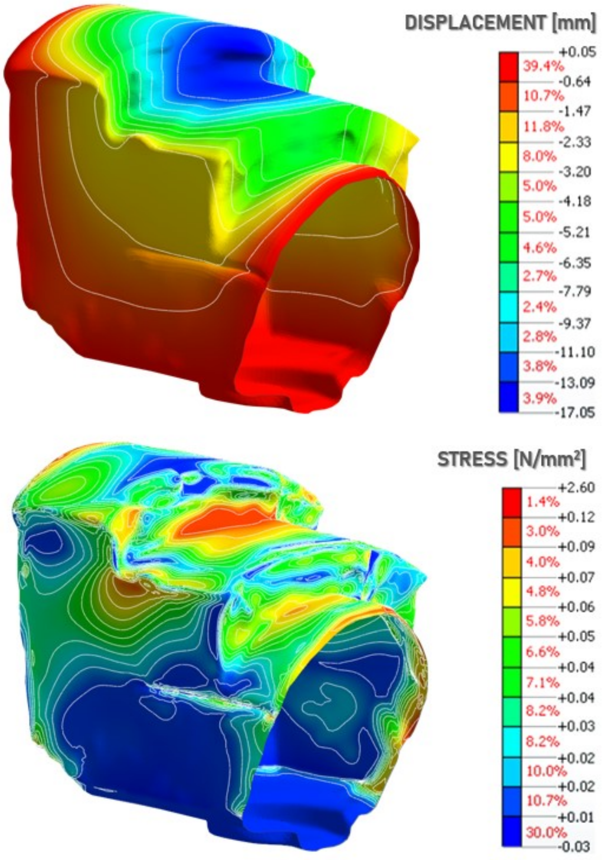


Figure 11. Results in terms of displacements and stress obtained from the FEM analysis of the subway.

4. DISCUSSION

The transformation from a TIN model to a quad-mesh polygonal model is an optimal process as it is able to generate a 3D surface model characterised by a smaller number of meshes while maintaining the accuracy required for subsequent FEM analysis.

In addition, the decimation and simplification process produce, as an output, a better performing model that is easily manageable in subsequent processing; however, these processes are not to be considered constant as they vary according to both the size of the object represented and its geometric complexity.

Another advantage of polygonal modelling consists in controlling the geometric quality of the resulting mesh. In fact, with this modelling approach, almost all possible problems related to mesh geometry are solved, i.e. intersecting faces, open edges, faces where the normal differs from the normal at the vertices and directions that differ from the global direction of the mesh: these aspects may affect the correct export of the model as well as create problems in classical Boolean operations with meshes.

The resulting model, simplified and geometrically correct, is easily interoperable with other processing and analysis software, and as it is not too large in size, it requires little computational capacity and thus meets the requirements of optimal model management.

5. CONCLUSION

In this manuscript, an integrated methodological approach has been described that, starting from a point cloud survey (CRP, UAV photogrammetry or TLS), allowed the elaboration of accurate and high-performance 3D models in the field of monitoring and conservation of the existing Cultural Heritage.

Through processing procedures and thanks to the implementation of appropriate algorithms to simplify and reduce the number of faces, it was possible to transform a TIN (Triangulated Irregular Network) model into a polygonal mesh model (quad-mesh).

In fact, this transformation makes it possible not only to simplify the geometries of 3D models, but also to create a suitable interchange format capable of having the modelled geometries automatically recognised by FEM analysis software. The main procedure described therefore relates to the management and optimisation of meshes, which, by moving from a TIN model to a quad-mesh model and then converting to NURBS geometry, makes it possible to obtain high-performance 3D models in a short time. These will be the digital input product for subsequent structural analyses.

Finally, in order to validate the geometries reconstructed in the polygonal modelling phase and characterise the structural behaviour of the investigated architectures, FEM analysis was conducted using Midas FEA NX software (MIDASoft, Inc., New York, NY). We recommend that the author makes use of this feature. If the author does not feel comfortable with it, he may choose to manually number the sections and subsections.

REFERENCES

[1] T. Kang, Scan to BIM mapping process description for building representation in 3D GIS, Applied Sciences 13(17) (2023), art. no. 9986.
DOI: 10.3390/app13179986

[2] M. Gordon, L. von Zimmerman, O. Haradhun, D. Campanella, M. Bräutigam, C. De Wolf, Digitising building materials for reuse with reality capture and scan-to-BIM technologies, in: A circular built environment in the digital age. C. De Wolf, S. Çetin, N. Bocken (editors). Springer, 2024, ISBN 978-3-031-39674-8, pp. 41.
DOI: 10.1007/978-3-031-39675-5

[3] D. Costantino, M. Pepe, A. G. Restuccia, Scan-to-HBIM for conservation and preservation of Cultural Heritage building: The case study of San Nicola in Montedoro church (Italy), Applied Geomatics 15(3) (2023), pp. 607-621.
DOI: 10.1007/s12518-021-00359-2

[4] P. A. Escudero, Scan-to-HBIM: automated transformation of point clouds into 3D BIM models for the digitization and preservation of historic buildings. VITRUVIO-International Journal of Architectural Technology and Sustainability 8(2) (2023) pp. 52-63.
DOI: 10.4995/vitruvio-ijats.2023.20413

[5] Y. Alshawabkeh, A. Baik, Integration of photogrammetry and laser scanning for enhancing scan-to-HBIM modeling of Al Ula heritage site, Heritage Science 11(1) (2023), pp. 147.
DOI: 10.1186/s40494-023-00997-2

[6] M. G. D'Urso, V. Manzari, B. Marana, A combination of terrestrial laser-scanning point clouds and the thrust network analysis approach for structural modelling of masonry vaults, Acta IMEKO 10(1) (2021), pp. 257-264.
DOI: 10.21014/acta_imeko.v10i1.1013

[7] A. Adami, L. Fregonese, M. Gallo, J. Helder, M. Pepe, D. Treccani, Ultra light UAV systems for the metrical documentation of cultural heritage: Applications for architecture and archaeology. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 42 (2019), pp. 15-21.
DOI: 10.5194/isprs-archives-XLII-2-W17-15-2019

[8] Q. Wang, J. Guo, M. K. Kim, An application-oriented scan-to-BIM framework, Remote sensing 11(3) (2019), art. no. 365.
DOI: 10.3390/rs11030365

[9] P. Martínez-Carricondo, F. Carvajal-Ramírez, L. Yero-Paneque, F. Agüera-Vega, Combination of nadiral and oblique UAV photogrammetry and HBIM for the virtual reconstruction of cultural heritage. Case study of Cortijo del Fraile in Níjar, Almería (Spain). Building research & information 48(2) (2020), pp. 140-159.
DOI: 10.1080/09613218.2019.1626213

[10] F. L. Furno, F. Pietrucci, C. Tommasi, A. Mandelli, Un modello informativo parametrico per il Duomo di Milano-Test e sperimentazioni. Archeomatica 4 (2017), pp. 22–25. [In Italian]
DOI: 11311/1027734

[11] M. Pepe, D. Costantino, N. Crocetto, A. G. Restuccia, 3D modeling of roman bridge by the integration of terrestrial and UAV photogrammetric survey for structural analysis purpose, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci 42(2) (2019).
DOI: 10.5194/isprs-archives-XLII-2-W17-249-2019

[12] V. S. Alfio, D. Costantino, M. Pepe, A. G. Restuccia Garofalo, A Geomatics approach in scan to FEM process applied to cultural heritage structure: The case study of the "Colossus of Barletta". Remote Sensing 14(3) (2022), art. no. 664.
DOI: 10.3390/rs14030664

[13] R. Kolluri, J. R. Shewchuk, J. F. O'Brien, Spectral surface reconstruction from noisy point clouds. Proc. of the 2004 Eurographics/ACM SIGGRAPH symposium on Geometry processing, Nice, France, 8-10 July 2004, pp. 11-21.
DOI: 10.1145/1057432

[14] N. Amenta, M. Bern, M. Kamvysselis, A new Voronoi-based surface reconstruction algorithm. Proc. of the 25th annual conference on Computer graphics and interactive techniques, Orlando, Florida, United States of America, 19-24 July 1998, pp. 415-421.
DOI: 10.1145/280814.280947

[15] G. Turk, J. F. O'brien, Modelling with implicit surfaces that interpolate. ACM Transactions on Graphics (TOG) 21(4) (2002), pp. 855-873.
DOI: 10.1145/571647.571650

[16] M. Kazhdan, M. Bolitho, H. Hoppe, Poisson surface reconstruction. Proc. of the fourth Eurographics symposium on Geometry processing, Cagliari, Italy, 26-28 June 2006.
DOI: 10.2312/SGP/SGP06/061-070

[17] S. Ji, L. Lei, J. Zhao, X. Lu, H. Gao, An adaptive real-time NURBS curve interpolation for 4-axis polishing machine tool. Robotics and Computer-Integrated Manufacturing 67 (2021), art. no. 102025.
DOI: 10.1016/j.rcim.2020.102025

[18] V. P. Nguyen, P. Kerfriden, S. Bordas, Isogeometric cohesive elements for two and three dimensional composite delamination analysis, 2013 arXiv preprint arXiv:1305.2738.
DOI: 10.48550/arXiv.1305.2738

[19] S. Herban, D. Costantino, V. S. Alfio, M. Pepe, Use of low-cost spherical cameras for the digitisation of cultural heritage Structures into 3D point clouds, Journal of Imaging 8(1) (2022), pp. 13.
DOI: 10.3390/jimaging8010013

[20] V. S. Alfio, D. Costantino, S. Herban, M. Pepe, A. G. Restuccia, From TLS data into H-FEM model based on the quad-mesh: the case study of romanian church. Proc. of the 2023 IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage, MetroArchaeo 2023, Roma, Italy, 19-21 October 2023, pp. 356-360.
DOI: 10.21014/tc4-ARC-2023.068

[21] P. Kuryło, P. Frankovský, M. Malinowski, T. Maciejewski, J. Varga, J. Kostka, A. Łukasz, S. Szymon, (+ 1 more author), Data exchange with support for the neutral processing of formats in computer-aided design/computer-aided manufacturing systems. Applied Sciences 13(17) (2023).
DOI: 10.3390/app13179811

[22] V. A. Nelyub, The stress-strain state evaluation of elementary carbon fibers with metal coatings. In Journal of Physics: Conference Series 1990(1) (2021), art. no. 012071.
DOI: 10.1088/1742-6596/1990/1/012071