



Original article

Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site



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ABSTRACT

The aim of this paper is to implement a novel Scan to BIM method applied to cultural heritage field to build 3D GIS model able to connect different databases and, as consequence, allowing a multidisciplinary approach. The proposed method was applied to the case study of a rock church located in the famous ceramics district of Grottaglie (Italy). To obtain the 3D GIS model of the structure under investigation, it was necessary to perform, as a first step, an integrated survey with Terrestrial Laser Scanner technology and close range photogrammetry which allowed the construction of a dense point cloud and high-resolution orthophotos useful for the study of architectural and historical analysis of the elements present within the rock site. Subsequently, the single objects identified using the stratigraphic method, was modelled from point cloud by the development of an original procedure based on the use of some tools developed in Rhinoceros and MeshLAB software that allowed reconstructing the objects in a geometrically accurate way. Indeed, the difference between the point cloud and the BIM model was of few millimetres, demonstrating the high quality of the proposed method. Finally, the BIM model was imported into 3D GIS environment and for each element previously identified, it was possible to connect multi-information.

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1. Introduction and aim of research

The digitisation of Cultural Heritage is an essential prerequisite for the proper conservation, management and enhancement of structures and landscapes present in the area. In recent years, the world of representation and the world of semantic content are increasingly intertwining; in this perspective, GIS (Geographic Information System) has represented the first step for the integration of geographical information connected to an object with semantics or data information [1]. Sometimes, instead of connecting to a geographical reference system, such as in case of a single building or a limited area, SIS (Spatial Information System) has been developed and especially applied in the field of cultural heritage [2,3]. In the GIS or SIS environment it is therefore possible to associate each territorial object with many fields or even connect, by relational databases, other tables referring to the object under consideration. However, the limit of such approaches is mainly related to their two-dimensionality; for this reason, 3D GIS has been devel-

oped, whose may be defined in very similar way to that of the 2D system, i.e., systems able to represent, manage, manipulate, analyse and support decisions based on information associated with three-dimensional phenomena [4,5]. Many works carried out on 3D data modelling have focused on the use of voxel (volumetric pictures elements) data structures [43]. However, this environment does not allow the construction of complex 3D surfaces; in fact, especially in the field of architecture and archaeology, the 3D reconstruction of objects requires the use of complex shapes, such as NURBS (Non Uniform Rational Basis-Splines) or curves or more in general shapes variable both in plane and elevation. Therefore, the digital recording of cultural heritage sites in a realistic way plays an important role.

Other 3D surface representation methodologies were presented by Nieto-Julián et al., 2019 [44] and discussed in Bruno, 2017 [45].

Dore and Murphy, 2012 [6] have developed a special approach for digitally recording cultural heritage sites called Historic Building Information Modelling, namely a system for modelling historic structures from laser scan and photogrammetric data using Building Information Modelling (BIM) software. The HBIM process involves a reverse engineering solution whereby parametric objects

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representing architectural elements are mapped onto laser scan or photogrammetric survey data. In general, once the geomatics survey has been carried out through close range photogrammetry (CRP) techniques or through Terrestrial Laser Scanning (TLS), the point cloud or its mesh (generated by the point cloud) are modelled into BIM objects [7]. From the point clouds to BIM model, several methods have been developed as shown in many works present in the literature [8,9,10,11]. Therefore, through the reconstruction of digital 3D models and, subsequently, the parameterisation of individual objects in the BIM environment, it is possible to associate physical-mechanical characteristics with each structural or architectural element and other imitated information. Nevertheless, if on the one hand it is possible to build very realistic surfaces in BIM modelling software, on the other hand it is not possible to use the standard libraries that are present in the different BIM software, such as in Revit software. Furthermore, the fields available in BIM environment for the storage and description of the elements is quite limited. 3D GIS environment, instead, allows building many fields and connecting many databases. The first applications of 3D GIS approach was described in urban environment as shown in Murata (2004) [12] who developed a 3D GIS application to visualise the existing state of cities and to perform simulations of the district development plan; in this application the high resolution 3D city model was introduced and combined with the 2D urban planning database. Again, in the urban context, especially in historic centres or cities of a considerable cultural and historical importance, 3D GIS have been used to model buildings and, at the same time, integrate different databases. Almedia et al. 2016 [13] presented the results of the 3D-GIS model developed for the Historic Centre of Leiria City (HCL) in Portugal, where the integration of 3D BIM model in a 3D-GIS environment was tested. Pepe et al., 2020 [14] used a GIS approach as a basis for the construction of multiscale 3D models of the old city of Taranto (Italy).

From the urban scale to that of the individual building or small area, 3D GIS models were applied in several case studies. Centofanti et al., 2011 [15] developed an architectural Information System called SIArch-Univaq which can be integrated with “Risk Map” Italian database; in this latter environment, 3D models were realised according to building constructive elements, derived from a critical architectonic surveying; the importation of models into GIS allows the interrogation of the constructive elements (i.e. beam, window, door, etc.). In the archaeological field, Trizio et al., 2018 [16] illustrated the results of an experimentation carried out in the medieval site of *Amiternum* (Italy) and the potential of the integration of three-dimensional digital models and 3D GIS. Another example in this field, it is reported in Landeschi et al., 2015 [17] where the authors described an innovative framework for employing 3D-GIS as an exploratory platform to perform visual analysis. Baik et al. 2015 [18] wrote about an approach for the integration of 3D Building Information Modelling and the 3D GIS to provide semantically rich models and, as result, the benefits from both systems to assist in documenting and analysing cultural heritage sites. Hence, in the context of digitisation of cultural heritage, the use of technologies, algorithms and methods based on 3D GIS is constantly growing. Likewise, the development of BIM and HBIM systems in the field of cultural heritage is increasingly important. Indeed, BIM-GIS integration is widely considered as a way forward for both domains. Karan (2014) [19] discussed the interoperability for BIM tools in the geospatial domain using semantic web technology. Ohori et al., 2017 [20] discussed geometric and topological issues for the integration of GIS-BIM data. Tsilimantou et al., 2020 [21] wrote about the importance of combining multidisciplinary data with the development of GIS thematic maps and HBIM. The methods and techniques for the integration of 3D GIS and HBIM are in continuous development and evolution in order to simplify the procedures for an efficient management of cultural heritage. In

this direction, Abd et al., 2020 [22] developed a procedure able to link GIS and BIM data using a smart platform called Autodesk InfraWorks to create the digital representation of the real world. Dakite and Zlatanova (2020) [23] proposed an automatic framework that allows to transform the local coordinates of a BIM model into real geographical coordinates, starting from a 2D geo-referenced polygon of the building. Therefore, considering the development of research in the semantic management of 3D models, the aim of the study is to implement a novel methodology able to integrate the data stored in BIM and 3D GIS environment in order to share, manage and archive in a digital and efficient way the cultural heritage present on the territory.

2. Method and data

2.1. Methodological approach

In order to achieve the objective of documenting and cataloguing the architectural elements present within the site under study and to obtain a high degree of detail, both from a geometric and semantic point of view, a new approach is proposed. Starting from a historical-bibliographical reconstruction followed by an accurate detailed survey, a three-dimensional model of the site integrated with a series of heterogeneous information that will form the basis of an RDBMS (Relational Database Management System) prepared for continuous implementation can be obtained.

The metric and documentary analysis of building of a particular historical, architectural or archaeological interest can be divided into the following phases:

- Historical analysis;
- Surveying and metric data processing 3D;
- Identification of characteristic elements and its modelling;
- Digitisation of semantic, documentary and graphic information.
- For the three-dimensional survey of architectural assets, as in the case of the survey of rock church, modern techniques that lead to an excellent result in terms of accuracy and quality of the data are essentially attributable to photogrammetric survey and TLS survey. Examples of TLS surveys in rock churches can be found in the following works [24,25] while applications of photogrammetric method can be found in Lesandro et al., 2018 [26] and Higuchi et al., 2019 [27]. While the active sensors of TLS instruments are able to generate dense clouds of remarkable quality in terms of precision and data density, in general with the spread of SfM and MVS algorithms it is possible to reconstruct a three-dimensional model using range-imaging techniques derived from Computer Vision (CV), using simple dSLR (digital Single-Lens Reflex) cameras. Therefore, in the process of survey of cultural and architectural heritage, generally characterized by complex geometries, the integration of the two different acquisition techniques and in particular the use of active sensors (high data density and acquisition speed) and passive sensors (texture quality and low cost) allow to obtain an accurate and detailed three-dimensional model.

A widely used method of investigation consists in dividing the analysed structure into stratigraphic units (in English-speaking countries it is called “Context”, in Italy “Unità Stratigrafica” (US), in some excavations “Stratigraphic Unit” (SU) (see Demetrescu, 2015) [28]. The application of the stratigraphic method to archaeology hails from Edward Harris’ experiences dating back to the mid-twentieth century [29]. Since the focus of this paper is a rising structure, USM (masonry stratigraphic unit) will be taken into consideration. In general, there are two different types of stratigraphic units: positive USM, if they result from a single constructive action, and negative USM, if they result from a removal action due to human action; some units may be defined as covering units if

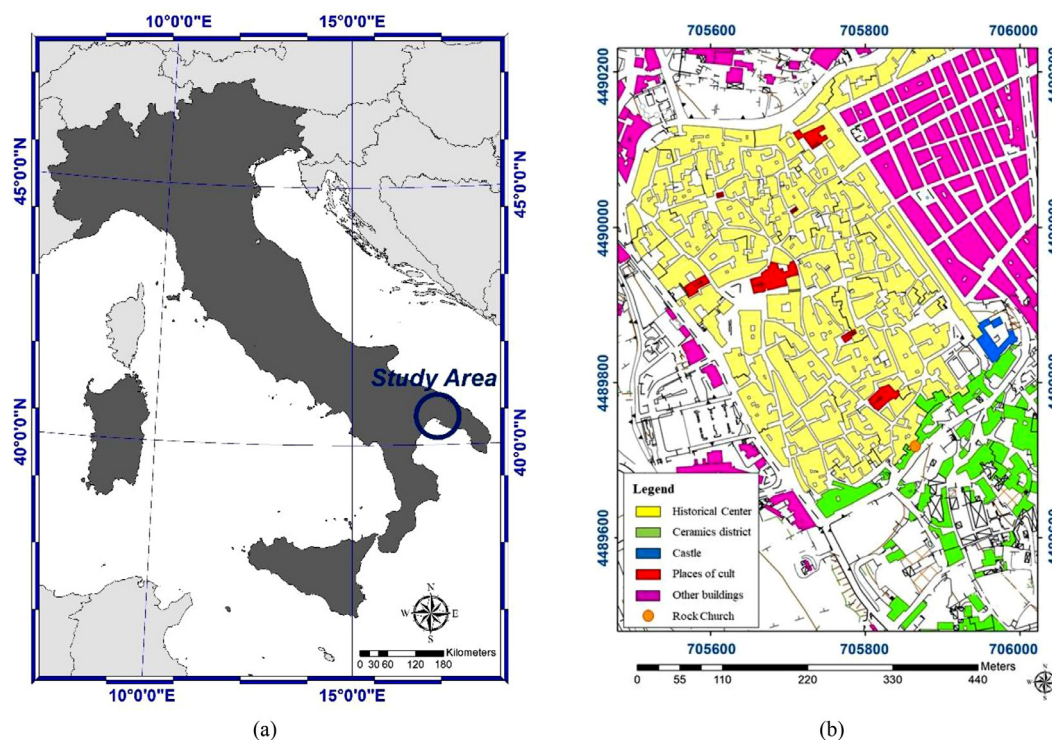


Fig. 1. Study area (a) and categorization of the Regional Technical Map of Grottaglie Town (b).

they cover other units, such as plasters, paints, wall coverings, and flooring [30]. The Stratigraphic Unit are also distinguished in primary units with a structural role (foundations, walls, vaults, arches and floors) and secondary or gregarious units (including, for example, floors, fillings, coverings, fixtures or false vaults) carried by the primary units: the secondary units cannot exist without the primary units and are always chronologically posterior. In addition, it is possible to define the unit in Italy called “Unità Stratigrafiche di Rivestimento – USR” the positive and gregarious US units that cover other primary units and constitute the finishes, such as plasters, stuccoes, mosaics and other complex floorings for decorative motifs or for the use of different materials [31]. The first research that related the US to the parameterised model in the BIM environment was conducted by Nieto et al., 2014 [46].

Once identified each stratigraphic unit, it is possible to perform an analysis with extraction of essential elements (CAD restitution), colour and/or geometry analysis. At the same time, it is possible to model and parameterise the individual units identified in HBIM environment. The method of reconstruction of 3D through profiles (see De Luca, 2011) [32] may be used to build 3D model. This method, starting from a set of 3D point cloud, allows reconstructing the 3D of an object or structure by the use of curve or a parametric surface. amongst the parametric representations of curve or surfaces, one of the most used are the so-called NURBS (Non Uniform Rational B-Splines) because it allows obtaining realistic representation [33]. To model a structure in a BIM environment, it is necessary to define the Level of Development (LOD) of the model. In these applications, a LOD400 level may be used. Indeed, in this level, the elements are graphically represented within the model as a specific system, assembled or modelled in terms of size, shape, position, quantity and orientation with details for manufacturing, assembly, installation and information. Semantics, image or other information may also be linked to model elements using a specific file. An application in Cultural Heritage environment is reported in Pepe and Costantino (2020) [34] where the different elements of an historical masonry

bridge are modelled in Rhinoceros software; these elements (parapets, arches etc.) are connected with a sheet (in Adobe pdf format) describing the state of maintenance and restoration works necessary for the conservation and protection of this bridge. Another application is described in Bruno and Roncella (2019) [35] where in Revit software, the elements of the Parma Cathedral are modelled and connected with other information, such as data from previous surveys, archival data, photographic images, data sheets about previous restoration activities. To achieve this aim, the authors developed a standalone specific-designed database linked to the 3D model of the asset and built with BIM software. If it is possible to add images, texts in the BIM environment, it is also true that these environments are not as flexible as those that can be implemented in relational databases. Indeed, some limitations are often binding, and a considerable interest is arising in the development of solutions to link BIM and external databases, allowing easier data management [36].

To overcome these limits, it is necessary to find a suitable environment able to manage different databases and connect them to spatial 3D objects. This means creating a relational model database in which the name of the stratigraphic unit represents the key field for the connection of the different databases. Key field, as is well known, is a set of attributes within a relational database table (also called a relation), such table does not have two distinct rows or records with the same values for these columns and this set of columns is minimal, i.e., removing any column from the key would result in duplicate values in the resulting subset.

A powerful set of tools that can collect, store, retrieve at will, transform and display spatial data from the real world is represented by GIS [47]. The 3D GIS system are capable of visualizing and managing 3D model generated in BIM environment. However, there are still few studies about data management in the integration of HBIM and GIS models [37]. Therefore, our proposed research aims to describe a new approach about the integration of HBIM and GIS environments; this approach was applied to the case study of the rock church discovered in Grottaglie (Italy).



Fig. 2. Main altar and frescoes (a); detail of the central fresco (b), detail of the cross incision (c) and of pharmacy engraving (d).

2.2. Site location and historical notes

The rock church is located in the town of Grottaglie, in Southern Italy (Fig. 1a), in the hinterland of the province of Taranto. The town, characterized by a high presence of lamas (erosive furrows typical of the Murge landscapes) and ravines, takes its name from the presence of numerous caves used as shelter and water gathering since the Palaeolithic age [38].

Around the urban fabric, in the eighteenth century the famous “Ceramics District” (artisanal area) was settled where a series of workshops curved into the rock still produce many ceramic products of ornamental and daily use (Fig. 1b).

The crypt, completely hidden by an ancient 14th century oven, was found in 2008 after the removal of the same oven (never used). From the excavation, considerable amounts of finds dating back to the 9th century A.D. were discovered. In order to access the crypt, it is necessary to go down some steps as the church is 2 m below the level of the garden.

The crypt is composed of a single nave composed of three side apses divided by four twisted columns, which enclose the altar, in turn composed of three arches carved into the rock on which three frescoes are located. The approximately dimensions of the building are (in planimetry) 4.00×3.30 m.

The central fresco depicts a blessing Christ holding in his left hand an open book with the Latin inscription “*ego sum lux mundi*”; the side frescoes depict instead St. Nicholas of Myra and St. Barbara that are characterized by finely decorated clothes (Fig. 2a and b). In correspondence of the altar, on the ceiling we find a circular engraving that contains inside a cross in relief: this engraving is widespread in many contexts of Taranto and Lecce and its purpose was to differentiate the liturgical space from the rest of the sacred environment (Fig. 2c). Researchers believe that the cross could represent a temple symbol given the position of the crypt near the “Via Appia” (about 200 m away).

In the front wall, it is possible to observe, delimited by another twisted column, a stoup dug into the rocky bench and frescoed by a sort of tree. The wall is completed by 16 niches in a quasi-square shape that, according to experts, represents a real pharmacy in which the monks stored the medicinal herbs (Fig. 2d).

Further excavations and archaeological investigations are revealing new spaces and corridors that lead to rooms adjoining the altar in which new frescoes have been found perfectly preserved.

In general, the crypt was part of a larger complex consisting of an ancient palace in which fragments from the 4th century B.C., floors from the Roman era and a colonnade from the 19th century that contains a beautiful garden were found.

2.3. 3D survey and modelling

The survey of the church was carried out with two different methodologies: photogrammetry and TLS. The goal of this approach was to generate a complete 3D model and to integrate the information coming from the two different survey methodologies.

After the inspection carried out in the area under study, the design of the photogrammetric survey was performed; in particular, the position of the targets was defined in such a way as to ensure a reference of the images for the next generation of the 3D model.

Considering the irregular shape of the church, it was decided to position targets along the side walls, others on the floor and finally on the vault of the church.

The photogrammetric survey was carried out using Structure from Motion (SfM) and Multi View Stereo approach (MVS) [39,40]. This approach solves the scene geometry without any need to specify a priori targets or check points in the acquired images and allows obtaining a sparse point cloud of the scene under investigation. MVS algorithm is used to increase the density of points starting from the point cloud generated in SfM process [41].

Table 1
Evaluation of errors on single scale bar.

Scale bar	Error [m]
1	0.003
2	0.003
3	0.008
4	0.001
5	0.003
6	0.002
7	0.009
8	0.002
Total	0.005

In practice, the image was acquired nadirally to the surfaces while maintaining an equal distance and ensuring that the images overlapped by at least 80%. In particular, this method was carried out along the side walls, for the apse with frescoes of an historical and artistic value, and for the floor and the vault. In order to better represent the frescoes and other valuable elements contained inside the crypt, more photos have been acquired to define them in elevated detail.

The photogrammetric survey was carried out by a NIKON D3300 with dSLR 24.2 Mpixel (23.5 × 15.6 mm CMOS sensor) and a fixed lens with a focal length of 18 mm.

Considering the poor lighting conditions, the camera was supported by a tripod; in this environment, an ISO sensitivity of 1600s and a fixed exposure time of 1/60 s were set.

Inside the church, 8 numbered targets contained in a 0.30 m metric bar have been positioned, useful for referencing and scaling the model. A total amount of 186 images was recorded.

In order to perform the photogrammetric process, the photogrammetric software 3DF Zephyr, developed and marketed by the Italian software house 3DFLOW, was used.

The data were processed at high resolution for both the sparse and dense point cloud process. For the scaling of the model, 16 GCPs were manually identified, in correspondence with the metric bars.

In the alignment step, conducted in high mode settings, a sparse point cloud of 338,068 points was generated. The total error, i.e. root mean square error for all the cameras can be calculated by following formula:

$$Total\ Error = \sqrt{\sum_{i=1}^n \frac{(d_{i,est} - d_{real})^2}{n}} \quad (1)$$

where $d_{i,est}$ is the value of the estimated distance and d_{real} the actual value of the distance between the two target centres of the metric bar used.

The total error achieved was 0.004 m with a reprojection error of 0.639 pixel. Table 1 shows the residual error values for each bar scale used. In particular, the errors on individual bars are below one centimetre and within a range of approximately 2 mm to 9 mm.

In order to build the dense point cloud even in the darkest areas, in addition to the photogrammetric survey, a TLS survey was carried out. Indeed, the photogrammetric point cloud was integrated, in the darker areas where the photogrammetric method did not allow obtaining a high point density, with the TLS. Naturally, a TLS survey was performed on the entire structure. In particular, HDS 3000 of Leica Geosystems (pulsed type of laser scanning system) was used (Fig. 3a and b). The TLS is a high-accuracy laser radar scanner with 360°x 270°field-of-view, equipped with video camera; The model surface precision is 2 mm from 1 m to 50 m of range.

The data acquisition was carried out in such a way as to guarantee a geometric homogeneity of the laser scanner survey both in terms of distance measurement accuracy and density of the 3D point cloud, positioning the scanner at an average constant distance from the area to be surveyed and choosing a scanning step based on the average distance. The post-processing of the TLS data was carried out by the Cyclone software. The fusion of the three scans was performed using 6 GCPs; the error on the individual GCPs was less than 1 cm. After filtering the data to eliminate some points considered outliers, a point cloud of 1758,729 points was generated, as shown below (Fig. 3c).

The two point clouds obtained by photogrammetric and TLS survey were compared in order to verify the quality of the geometries acquired with the photogrammetric method over the entire area of interest. In particular, a global recording of the two point clouds was first performed by applying the ICP (Iterative Closest Point) algorithm, which recalculates the transformation parameters reducing the distance of the homologous points. In particular, assuming that the two point clouds TLS and PHO (photogrammetric) are already approximately well aligned, the algorithm is based on the assumption that the corresponding points are the closest between the two datasets.

The T -transformation (roto-translation) that binds TLS to PHO has therefore been determined by minimizing the following quadratic function:

$$\sum_{i=1}^N \|TLS_i - T(PHO_i)\|^2 \quad (2)$$

The global residue was estimated with a standard deviation of 0.006 m.

In order to obtain the comparison between the two point clouds, after the application of the ICP (Iterative Closest Point) algorithm, the Cloud-to-Cloud (C2C) distance methods was used.

The average distance was 0.004 m and its variance is less than a millimetre; this means that the two point clouds can be superimposed and integrated with each other.

2.4. Building orthophotos, CAD representation and style analysis

From the point cloud, it is possible, through a series of processes, to obtain high-resolution orthophotos using images processed with photogrammetric techniques. In this process, the input data is exactly the point cloud: a triangulation TIN (Triangulated Irregular Network) surface is created starting from the metric information contained in each single point. In a TIN model, the points represent the vertices of a 3D triangle that model the surface, connected to each other and arranged irregularly in space.

Subsequently, once the triangular mesh is obtained, it was possible to parameterize the texture using different algorithms that take into account the geometry of the mesh itself; starting from the available photogrammetric dataset, it is also possible to select only some of the images to obtain a high and accurate quality of the texture. In this case, from the point cloud, it was possible to obtain a mesh composed of 3391,023 triangles. After obtaining the three-dimensional textured model, it is possible to generate a series of high-resolution orthophotos and in the context of the current practical application, to project the orthophoto on planes set by the user. In order to perform the orthophotos on the texturized mesh, an editing on the meshes was performed. In other words, only the area of interest was cropped and any triangles considered outliers were eliminated. In the case under investigation, once that section planes and projection plans have been properly defined, it was possible to generate orthophotos at different levels of height and internal elevations of the crypt on different façades. The orthophotos with a Ground Sam-

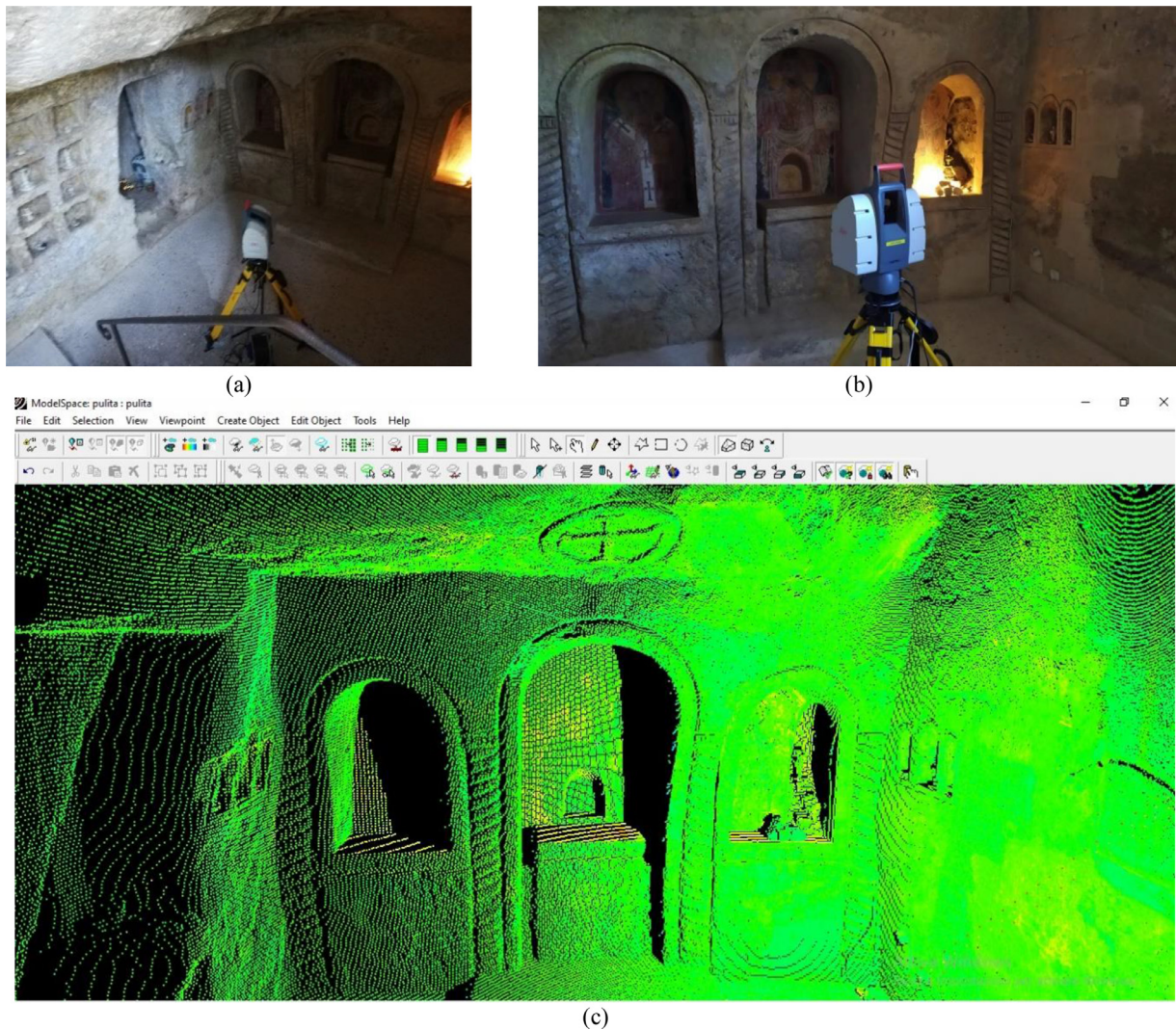


Fig. 3. Survey by TLS: TLS used for rock church survey (a, b), viewing in Cyclone software of the point cloud (c).

ple Distance (GSD) of 2 mm was generated. In addition, importing the orthophotos in Computer-Aided Design (CAD) software, it was possible to obtain a representation of the key elements of the frescoes. By analysing the prevailing colours of the frescoes (see Fig. 4) it was possible to identify the style of representation.

From a stylistic point of view, the frescoes are to be framed in the complex and articulated Apulian artistic tempery (the particular character of a given environment or cultural and historical moment, considered in relation to events that are its result or expression) of the first half of the 14th century. In fact, they appear as a conservative product, linked to the local Byzantine tradition still partly influenced by the late-Commeni models, namely an inevitable artistic reference point for the whole Ionian territory, from which the unknown author inherits the frontality, the staticity, the rigid drapery of the figures and the richness of the garments. The first elements of the new French style, can be seen in some details, such as the perfectly oval minds marked by a fold of the skin, the slender necks, the accentuation of the agmidal shape of the eyes and the hinted complexion of the cheeks. As far as the stoup is concerned, it is ichnographically unique in the Apulian territory and at the moment there are no direct comparisons that would allow a univocal reading.

2.5. Identification of the objects and BIM modelling

Thanks to the study of the orthophotos, the analysis of the style and the colours of the frescoes present in the building, it was possible to identify each element of the structure. Therefore, starting from the cloud of points, the single elements of the structure identifiable through the stratigraphic method were modelled.

The individual stratigraphic units identified in the rock church by an expert archaeologist are:

- the wall with the 3 niches was named USM1;
- the columns with the carvings were assigned US1A, US1B, US1C and US1D;
- the Templar cross was named US2;
- the 3 frescoes were classified as USR1, USR2, and USR3;
- the access staircase in the church with USM3;
- the wall opposite the 3 niches was assigned USM2 and USM4;
- the fresco contained in the niche of USM2 was assigned USR4;
- the column (near USR4) was assigned US3

The modelling of the single units of the structure was performed through the Rhino 7 Inside Revit software. In particular, the realisation of the three-dimensional restitution of the structure under investigation was developed in two phases.

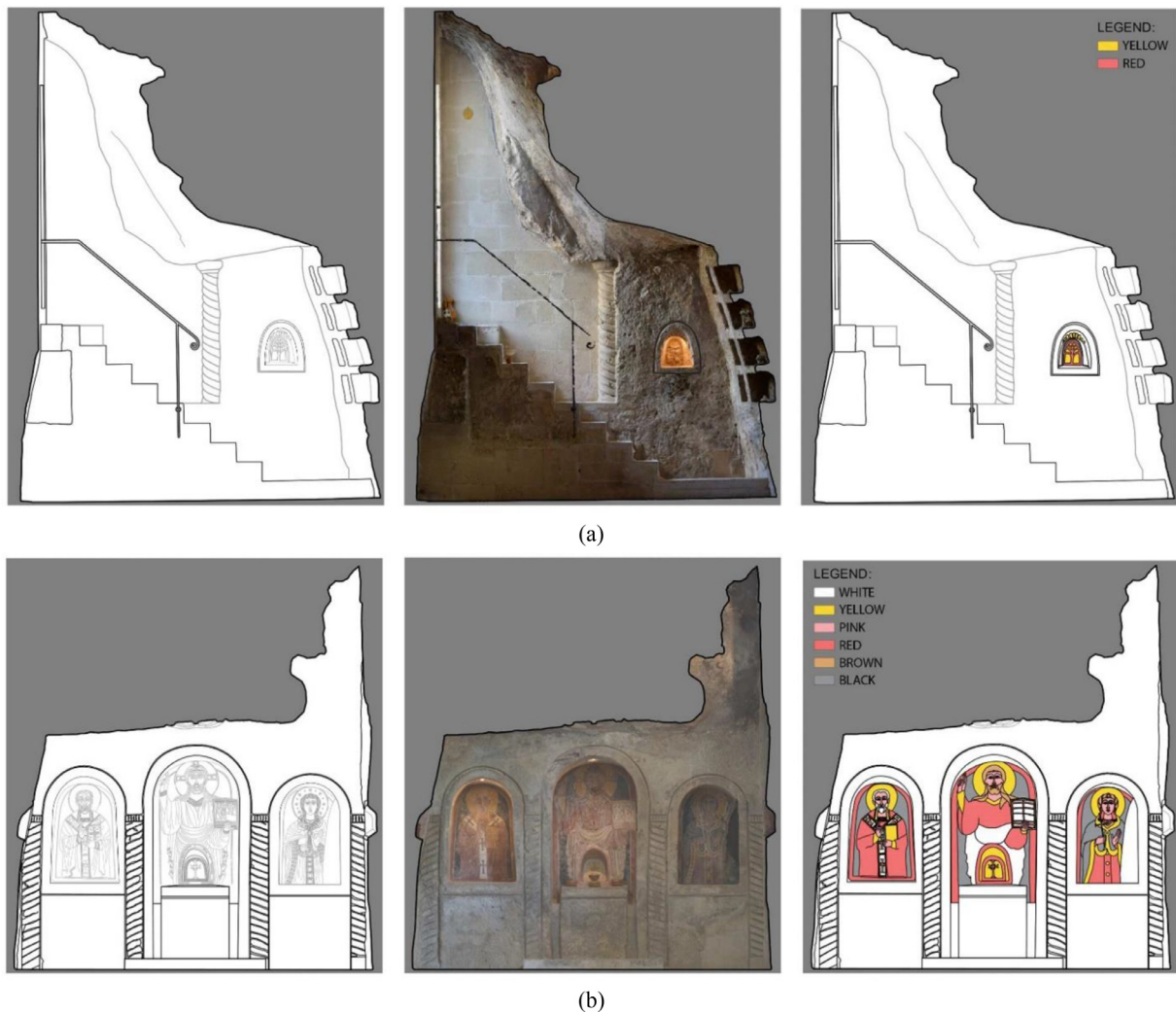


Fig. 4. Orthophotos, CAD representation and colours of the frescoes in the entrance of the rock church (a) and in the wall showing the three religious icons (b).

The first phase started with the import of the point cloud (in *.las ASPRS format) through the dedicated arena Veesus plug-in for McNeel's Rhino software v7. Through this latter plugin, it was possible to control the point cloud, reduce noise, control shades etc.; it was also possible, moreover, to rotate the point cloud and adapt it according to desired directions. Through a series of section planes, completely controllable in space, the point cloud was sectioned. All realised sections were transformed into 1D geometric elements such as splines and polylines. The 1D lines through two-dimensional modelling commands were transformed into 2D entities i.e. NURBS surfaces. Finally, for some of the architectural-monumental elements it was possible to switch from 2D surfaces to 3D solid models. In addition, the construction of the model was carried out using various Boolean commands. Due to the complexity of the structure characterised by abrupt surface changes, a very high number of sections had to be created and it was necessary to use a very advanced 2D entity generation tool (NURBS surface), the loft command, belonging to the *evolute* plugin, which is able to reconstruct highly irregular NURBS surfaces by readjusting them. Through this procedure, it was possible to identify the sections of both the entire natural part of the ceiling (natural rock) and the specific architectural parts required, such as the niches, the surfaces of the niches containing the frescoes, the Templar cross, the staircase and the twisted columns.

For the modelling of the completely natural rock the procedure with the realization of the horizontal sections was very complex. Consequently, the file containing the modelling of the structure built in Rhino was very heavy from the computational point of view. It was therefore decided to proceed with the modelling of the entire structure using a new procedure (phase 2). This procedure was articulated in the following steps:

- Importing the point cloud into a very advanced mesh creation software, namely Meshlab [42] that is an open source system for processing and editing 3D triangular meshes;
- Mesh modelling in that environment using different tools for the management of the point cloud, such as the creation of normal;
- importing the mesh into Rhino 7 where it was automatically placed in the same position as the point cloud;
- transformation of the triangular mesh in a quadrilateral mesh (quad mesh) in order to increase the manageability of the mesh both in the creation of renders and in the import of high precision models in BIM software;
- transformation of the quadrangular mesh into a single NURBS surface able to describe the 3D shape of the rock church;

At the end of the process, the results of the two methods were merged inside Rhino software.

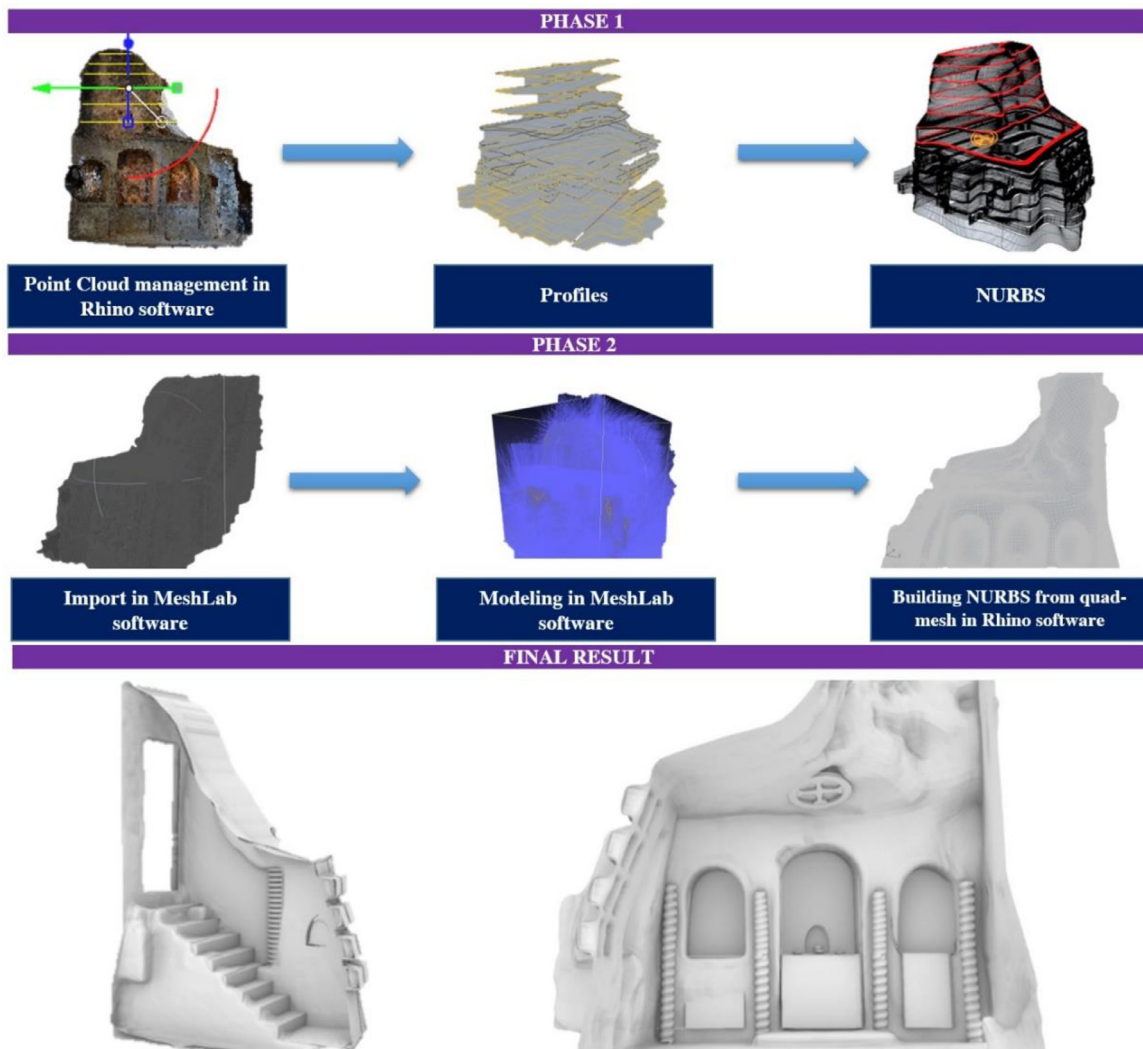


Fig. 5. Several stages for BIM modelling in Rhino 7 software.

Finally, the NURBS surface of the structure was cut with oblique sub-vertical planes to cut out the parts inherent to the niches and staircase area; subsequently, this surface was used for the definition of the architectural-monumental objects already realized in phase 1. The different steps just described are summarised in Fig. 5.

In order to evaluate the quality of the realized BIM model both from the topology and from metric point of view, it was necessary to perform a scan-to BIM validation [48,49].

Regarding the topology aspects, the several 3D structures realized do not intersect each other. The non-intersection is a direct consequence of the method itself with which the structural elements were realized, such as the extrusion of splines (curves) directly obtained from the intersections of planes with the point cloud. The intersection lines are therefore generators of multiple surfaces that are in contact with each other but cannot intersect.

The "Rhino.Inside.Revit" plugin has made it possible to transform the model generated with Rhinoceros software into Autodesk Revit® software. Indeed, Grasshopper's revolutionary programming language allows the transformation of objects, as shown in Fig. 6. In this way, it was possible to obtain the BIM model of the structure. The workflow just described is reversible, i.e. a model created in Revit can be transferred to Rhinoceros through a different programming structure in Grasshopper.

Geometric validation was performed by comparing the mesh obtained through modelling in Rhino software with the point cloud generated in the geomatics survey. In other words, Cloud-to-Mesh (C2M) distance was performed in Cloud Compare software, as shown in Fig. 7. The results of the comparison between the point cloud and the mesh show that the distribution of most points is within a range of 0.008 m with a standard deviation value of 0.004 m.

2.6. Integration of the BIM model in Esri ArcScene

Each modelled object parameterised in Rhinoceros was placed in an appropriate layer. Each layer was saved in a file suitable for import into Esri ArcScene. In particular, the extension of 3D Studio Max (*.3ds) was used for the export. Subsequently, using the tool implemented in ArcScene called "Import 3D Files" it was possible to build a specific scene layer. In this way, it was possible to assign to each geometry many fields that can describe the properties of the individual object from an archaeological, architectural and physical point of view. In the case study, the following fields were taking into consideration:

- "photo" to visualise the object;
- "photo" to visualise the orthophoto;
- "text" to describe the properties of the material;
- "text" to describe state of preservation;

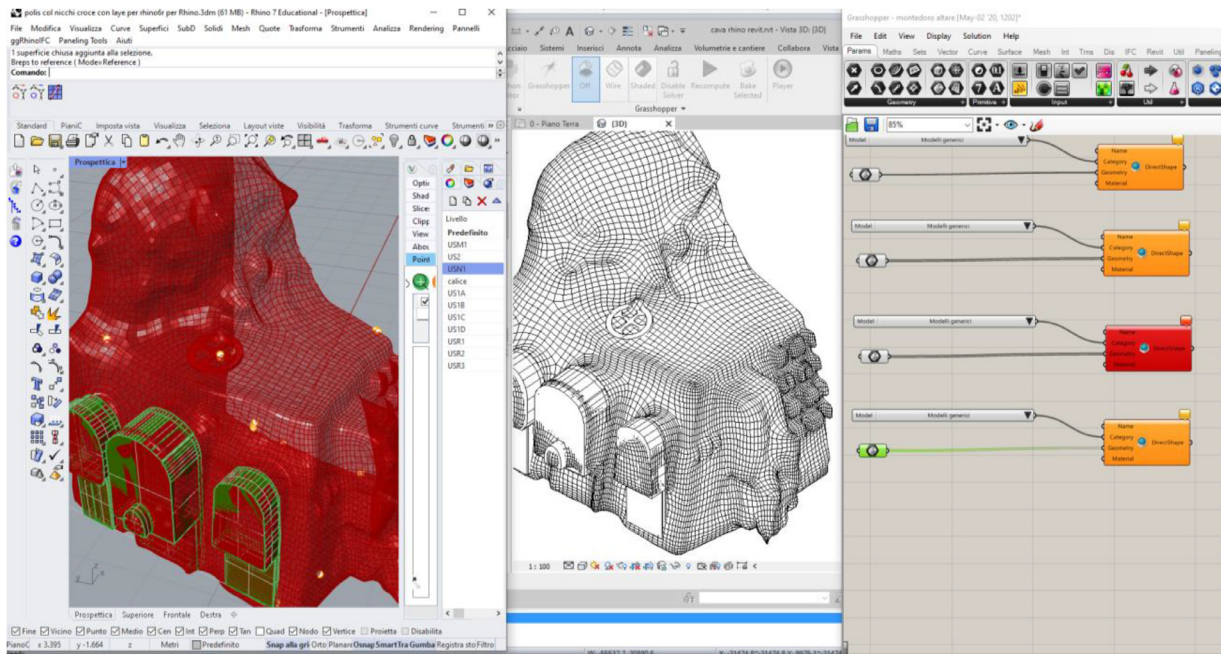


Fig. 6. Transformation of parameterized objects from Rhino to Revit through Grasshopper software.

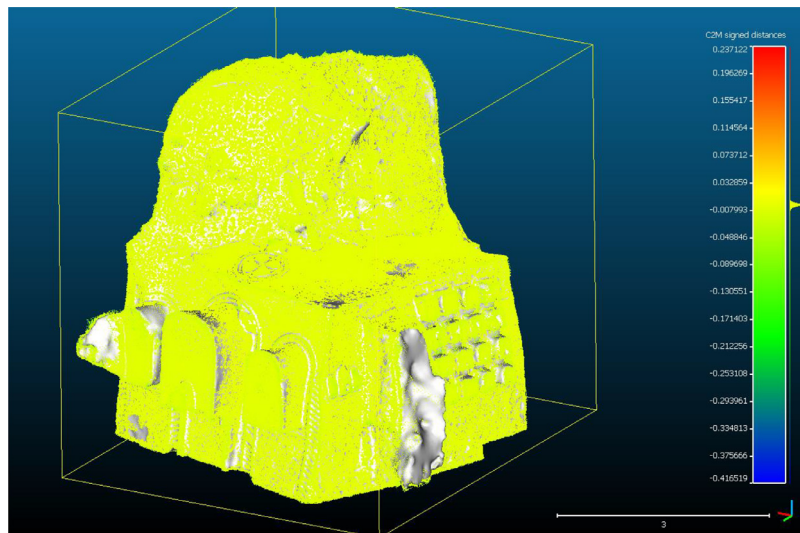


Fig. 7. C2M comparison on the whole structure.

- “text” to build a hyperlink to archaeological sheet;
- “text” to build a hyperlink to visualize or download the point cloud in Adobe Acrobat format.

The final model built in 3D GIS environment with the visualisation of information related to a stratigraphic unit of coating (USR3) is shown in Fig. 8.

3. Discussion

The modelling of individual objects involves a preliminary and multidisciplinary study. In fact, as shown in Pepe and Parente (2017) [3], the SIS in Cultural Heritage environment can be defined as a “set of skills and competencies that can manage the archaeological and/or Cultural Heritage data taking into account their multidimensional coordinates. This means converging different skills in a single environment where archaeologists, historians, architects,

geomatics, engineers can share, analyse and manage different information. The link between the different information produced by each expert involved in the project is ensured by the identification of a common identifier (primary key). For example, the use of stratigraphic units makes it possible to discretise and identify each object that is of strategic importance for the understanding and analysis of the archaeological or architectural artefact. In this way, as occurs in relational databases, it is possible to link many tables. In addition, the possibility to manage the information of 3D objects in the BIM and SIS environment allows users not only to have a more direct view of the study environment but, at the same time, to obtain further parametric information of the objects (materials, surfaces, volumes).

Based on the three-dimensional modelling, each modelled object assumes a value within the structure: using the stratigraphic method, each element is associated with a unique code that represents a certain “ID” within the relational database.

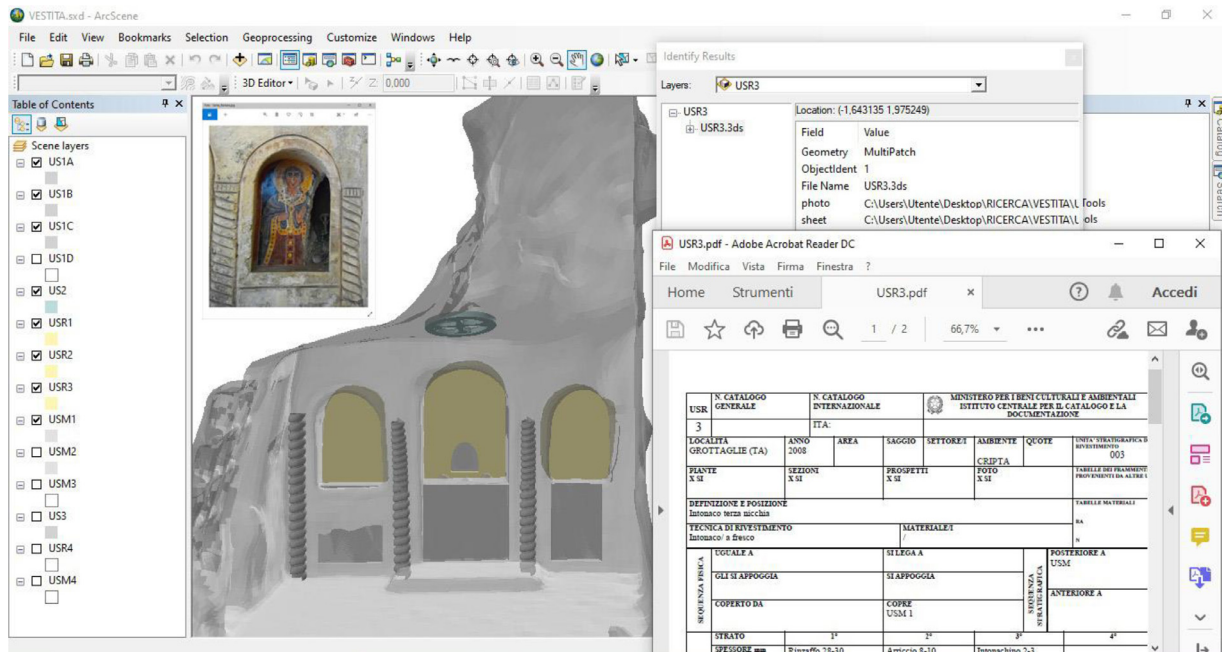


Fig. 8. Screenshot of the ArcScene environment built for efficient management of the attributes of individual object.

The realisation of an RDBMS constructed in this way allows, through the creation of appropriate links, the development of a system capable of managing, visualising and interrogating the heterogeneous information of any type of 3D object. An important aspect of relational databases is the possibility of querying the RDBMS and assessing the spread of similar characteristics on the territory; it is therefore possible to relate objects, paintings, elements and archaeological evidence that are similar but belong to different elements, within the structure of the database. Through the insertion of appropriate codes and attributes within a table, it is possible to relate multiple common features to other architectural sites in the territory that present elements or characteristics common to those of reference, and ultimately obtain a series of thematic cartographies that represent a map of their diffusion. In this way it is possible to interrogate the database and to identify other places where a painting has similar characteristics to the reference one or, as in the case study, it is possible to trace which other rock-hewn churches present architectural elements of a particular interest such as the Templar cross.

4. Conclusions

The method described in this paper has made it possible to obtain a parameterised 3D model with the enormous potential for integration of this model within 3D GIS software, such as ArcScene, where each object can be associated with multiple information.

The modelling performed on the point cloud in Rhino environment represents a key role in the construction of object surfaces. In this environment, in fact, it was possible to have a faithful reconstruction of the objects through the various tools developed within the software. To achieve this aim, a novel procedure was developed. This procedure enabled it to model even complex and irregular surfaces, such as the structure described in the case study shown in the manuscript.

The method proposed and described in the paper allows overcoming the limitations present in the management of information in BIM software, such as the material management of individual structural elements; currently materials with physical/thermal properties can be assigned in Rhino or BIM platform. For example,

the Revit family matching can be done only if the objects are standard: walls, floors etc. If the structure is a highly irregular solid, the users can assign the materials but cannot create a family in Revit but recognize it as only a generic mass, parametrizable with only one semantic characteristic.

In addition, the number of meshes built in Rhinoceros environment is lower than meshes generated in SfM-MVS environment or generated by a TLS survey. Indeed, this approach has brought to the construction of a parametric model much lighter in the management than the one obtained from the mesh model built on the whole point cloud.

The subdivision of objects within the structure, for example the incisions shown in the masonry, were therefore individually parameterised and defined using the US. The name of each layer was inferred using the stratigraphic method, i.e., by assigning a unique code (USM, USR, etc.). This code represents, within the 3D GIS, the key field for the relational database; to each element, it is possible to associate multiple information.

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