TLS survey for material analysis and classification of marble pavement of the “Cappella di San Cataldo” in Taranto (Italy)

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Abstract
The aim of this manuscript is to classify, from a material point of view, the marbles that make up the flooring of the chapel inside the Cathedral of San Cataldo in the city of Taranto (Italy). To achieve this aim, a 3D survey was carried out by Terrestrial Laser Scanner (TLS); indeed, the dense point cloud was subsequently classified according to the reflectance value. This task allowed to reconstruct the geometry of the various elements that make up the pavement and, through an accurate photographic interpretation, associate each geometry with the relative material. In addition, in order to create a useful tool for the conservation, valorization and enjoyment of the cultural heritage, as well as for possible maintenance and historical restoration activities, a model was implemented in a Spatial Information System (SIS) environment in which, in addition to the geometric information, a series of semantic-descriptive information on the materials was associated for a greater and more shared knowledge of the territorial Cultural Heritage.

Keywords
S.I.S., marble pavement, TLS, classification, reflectance, Cultural Heritage

1. Introduction

Cultural Heritage (CH) is an important historical, artistic, and architectural testimony that characterizes and defines the identity of a community or territory. This heritage also includes works of art, monuments, historical buildings that have been handed down by different past generations and are still the result of centuries of human interactions and cultural exchanges that have enriched the social and cultural fabric of a geographical area. The preservation and enhancement of this heritage, in addition to keeping memory and historical continuity alive, plays a crucial role in sustainable development, enhancing cultural tourism and contributing to the economic growth and social cohesion of the territory.
Therefore, aspects of management, monitoring and valorization must become an indispensable tool to improve the maintenance and conservation status of these cultural resources with the additional objective of digitizing, cataloguing, and archiving a range of heterogeneous information useful for the long-term preservation and protection of the historical heritage.
In this field, geomatics plays an important role as, through surveying and 3D modelling techniques, it enables the elaboration of accurate three-dimensional digital models in very high geometric resolution, which become the main support tools for maintenance, restoration, enhancement, and dissemination activities. Moreover, the advanced development of new and

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increasingly high-performance acquisition sensors and Artificial Intelligence (AI) algorithms allow, together with the most widespread acquisition techniques such as photogrammetry [1], [2] and 3D scanning [3], [4] to obtain photorealistic models suitable for restoration purposes, scientific and educational dissemination, tourism promotion, etc. [5].
For the reconstruction of a 3D model, both the type of sensor used, and the different digital surveying techniques and methodologies play a crucial role. In this context, by adopting one of the various types of sensors available, the result of the three-dimensional survey of a specific object is the "point cloud", i.e. a collection of millions of points characterized by information such as position (x, y, z coordinates), color (RGB tern), intensity and other scalar quantities, which preserves the original geometric information in 3D space referring to a given coordinate system [6]. The characteristics of geometric resolution, metric accuracy and definition of a point cloud depend on the type of sensor used; moreover, depending on the nature of the light that is employed, if it is natural light, the measurement methods are said to be "passive" (cameras, thermal imaging cameras, etc.); if, on the other hand, the light is encoded in such a way as to play a role in the measurement process, they are "active sensors" (laser scanners, structured light projection instruments, radar, etc.). Therefore, the choice of the sensor to be used and the surveying techniques to be adopted are also a function of the characteristics of the surface to be surveyed, as well as a function of the accuracy and geometric resolution required in the application [7].
Through the use of these geomatic survey techniques, it is possible to elaborate 3D geometries to which a series of thematic information can be associated and to develop interpretative models capable of classifying the object under different points of view (technological, material, structural, conservation and maintenance) and with a multi-temporal character [8].
Starting from the outputs obtained from different geomatic acquisition techniques and in the field of material characterization, numerous applications have been conducted in the field of cultural heritage; through a photogrammetric approach, Fioretti et al., 2019 [9] developed a 3D model and a series of orthophotos in order to classify the lithology, provenance and historical period of the Roman marbles and other decorative stones of the churches of San Sabino and San Giacomo in the city of Bari (Italy). Furthermore, for the flooring of the Basilica of San Nicola in Bari (Italy), it was possible to distinguish the original areas of the mosaic from those that have been heavily reworked over the centuries and finally identify the areas that have undergone restoration [10].
In the information context, G.I.S. (Geographic Information System) nowadays plays a major and growing role in the field of CH [11]. In fact, with this technology it is possible to build dynamic information management systems by associating a series of semantic and heterogeneous attributes with the geometric content, in order to implement a spatial geodatabase capable of processing, managing, storing, querying and sharing all the information collected [12].
For Cultural Heritage applications of G.I.S. technology, it is more appropriate to refer to Spatial Information Systems (S.I.S.) since local reference systems are typically used to position the acquired data, and geographic coordinates can serve as supplementary information to place the objects within a broader context. In other words, S.I.S. is a virtual environment where various types of information can be linked to specific points in a recognized spatial reference system.
In this area of research, Coli et al, 2021 [13] starting from an implementation of 2D data in a G.I.S. environment, the authors analyzed and characterized the marbles of the Saint John Baptistery in Florence (Italy) as geometric, geological and historical data, implementing a spatial geodatabase that can be managed via web through smartphones, tablets and PCs for querying and/or updating the data, thus representing a useful management tool in the field of preservation of historical-cultural buildings.
Iandelli et al., 2021 [14] using opensource, desktop and mobile solutions, and starting from the photo-interpretation and in situ survey, they realized in a G.I.S. environment a lithological

mapping of the coatings of various monuments (Duomo di Firenze, Campanile di Giotto, Duomo di Prato); furthermore, with the implementation of a structured database, the workflow included a mobile and opensource solution that allows the verification and management of the database in the field, i.e. a useful support tool in the field of conservation, dissemination and creation of virtual tours in the field of CH.

In this context, the aim of this manuscript is to identify a suitable methodological approach that allows, starting from a TLS survey and interpreting the reflectance values, to produce a metric model of the marble pavement of the Cathedral of San Cataldo in Taranto (Italy), identifying, classifying, and categorizing from a lithological-petrographic point of view the materials that make up the pavement itself.

2. Case study

For the analysis of the marble flooring, an experiment was conducted inside the cathedral of San Cataldo in the city of Taranto, Italy and built in the Byzantine era in the second half of the 10th century. Remodeled several times over the years, it was finished in the Norman era and the Baroque façade was completed in 1713.

The cathedral measures 84 meters long and 24 meters wide, and has a central nave, two side aisles and a single-nave transept. The three naves are divided by a double row of eight columns surmounted by capitals of varying construction, some of them reused from ancient buildings no longer in use.

In particular, inside the cathedral, on the west side of the north transept, there is a room dedicated to the saint and called the “Cappellone” dating back to 1151 and renovated in the 18th century [15]. The chapel has an elliptical plan with a major axis measuring 15.50 meters and a minor axis measuring 8.50 meters. It is preceded by a quadrangular vestibule and is entirely covered in polychrome marble, a decorative element typical of Neapolitan Baroque churches, while the ceiling is decorated with a fresco dating back to 1713.

These spaces have a rich decorative appearance characterized by a polychromatic marble in “opus sectile”, both for the floor and wall slabs; this is an ancient artistic technique that uses cut marble to create inlaid floor and wall decorations. This chapel represents a uniqueness in the Apulia region for its marble decoration that proceeds downwards from the cornice on which the dome is set [16] until it reaches the floor (Figure 1).

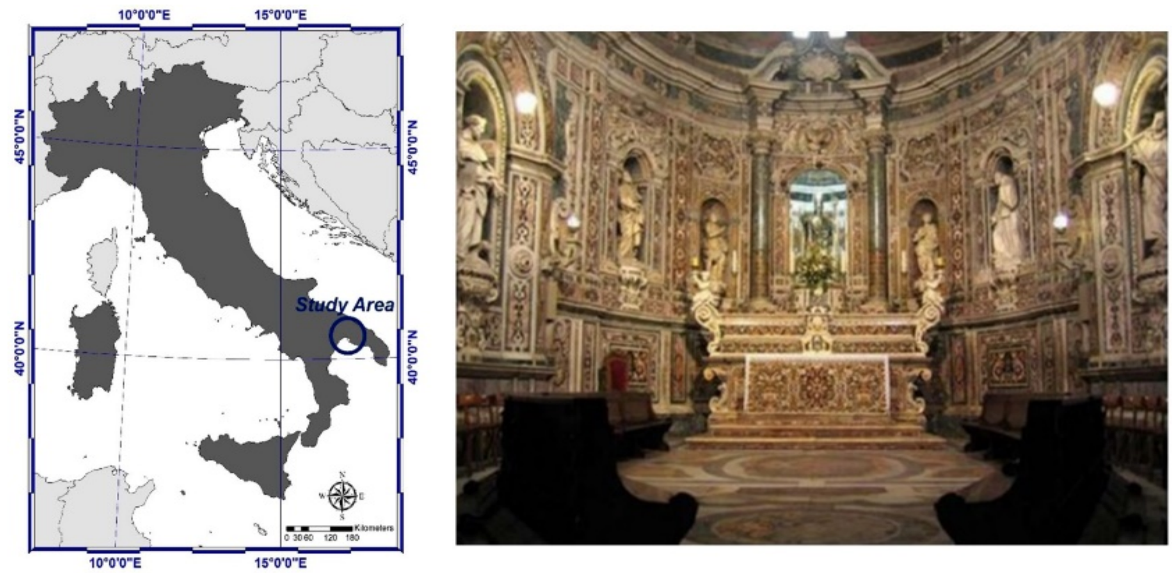

Figure 1: Location of the study area and details of the marble decorations of the San Cataldo Chapel in Taranto (Italy).

3. Method and Materials

3.1. Methodological Approach

The census and cataloguing of marbles in an environment can be performed through the following main steps: i) 3D geometric survey, ii) data classification and iii) vectorization and S.I.S. implementation. The geometric survey can be performed with sensors and different acquisition techniques. In the case study it was performed with phase measurement instrumentation. The point cloud generated can be classified according to the reflectance value in order to automatically classify different types of marble. The integration of this information with other documentation (historical, photographic, etc.) makes it possible to create polygons in a G.I.S. software; these polygons, thanks to the tools available in G.I.S., make it possible to implement the geometric data with multiple attributes that characterize the marble types.

3.2. TLS survey

Depending on the distance acquisition principle, TLS can be classified as time-of-flight (TOF) or phase measurement (PS). In the first case, a pulse is sent to the object, part of this pulse is reflected from the object's surface and returns to the scanner; in the second case, alternating frequency laser light is emitted and the distance to an object is determined by measuring the phase difference between the emitted and reflected signals. In both cases, the absorbed or reflected power can provide useful radiometric information to assess the change in properties of the scanned surface [17].
The TLS survey was performed with Leica HDS4500 instrumentation, which is a phase difference scanner with an acquisition capacity ranging from 100,000 to 500,000 points per second. This instrumentation is a short-range scanner with a field of view of 360 x 310 degrees. The main features of this equipment are outlined in Table 1.

Table 1
Characteristics of TLS instrumentation used for point cloud acquisition.

LASER SCANNING SYSTEM	
Type	Phase-shift
Colour	Red (visible)
Minimal Range	0.1m
Maximum Range	53.5m
Single Point Accuracy Position (at 10m)	
20% reflectivity (dark grey)	≤ 7.6mm ≤ 16.1mm
100% reflectivity (white)	≤ 7.2mm ≤ 13.7mm
Single Point Accuracy Distance	
20% reflectivity (dark grey)	≤ 5mm +360ppm*
100% reflectivity (white)	≤ 5mm +120ppm*
Angle (Horizontal/Vertical)	350 micro-radians
Target Acquisition Accuracy	φ ≤ 2mm ≤ 3.5mm

In order to survey the entire room, two scans were made, one at the altar and one at the entrance to the chapel. Using Leica proprietary management software, the two scans were recorded using 4 reflective targets at the TLS wavelength and 6 natural targets (Check Points) as reference points. The Mean Absolute Error value obtained from the merge phase of the scans was 0.005 m.

Figure 2 below shows the point cloud obtained in the survey phase and the detail of the natural and reflective targets used in the registration phase of the two scans.

3.3. TLS data classification

After the registration phase, the entire point cloud was imported into the Cloud Compare software [18]. The objective of this phase was to obtain an orthophoto classified according to the different shapes and types of marble that make up the pavement. TLS measurements are closely influenced by the reflectance of materials; indicating with $d\theta_r$ the reflected radiant flux and with $d\theta_i$ the incident radiant flux, reflectance can be defined as:

$$\rho = \rho(\lambda) = \frac{d\theta_r}{d\theta_i} \tag{1}$$

where:
ρ indicates the portion of reflected energy;
λ indicates the wavelength.

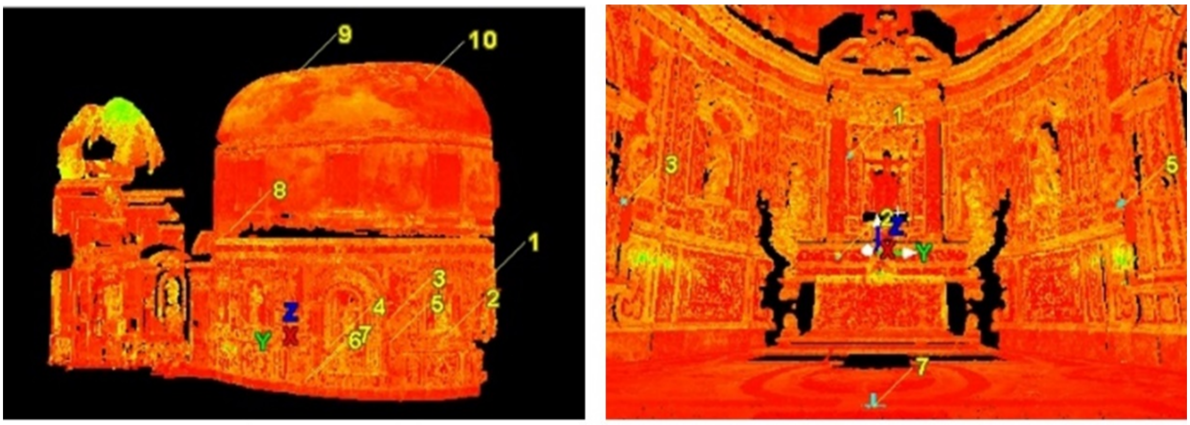

Figure 2: Identification of targets and detail of the point cloud obtained from the TLS survey.

In fact, the reflectance measurement depends on the type of surface and the value obtained varies depending on the angle of reflection, which in turn is influenced by the roughness of the object. Roughness is relative to wavelength: generally, smooth surfaces reflect in a specular manner (the angle of incidence is equal to the angle of reflection), while completely rough surfaces behave as Lambertian reflectors (the direction of reflection is independent of the direction of incidence). This is why it can be seen that smooth, light-colored materials have reflectivity of between 70% and 100%, while in rough, dark materials it can be as low as 20%. Furthermore, diffraction optics phenomena can occur in TLS scanning, from which it is possible to relate the degree of crystallinity of the materials to the reflectivity value. In fact, according to Costantino et al., 2021 [19] it can be seen that the incident laser light beam is refracted more by materials with a higher degree of crystallinity than by less crystalline or amorphous materials. Based on this information, the point cloud was then classified in Cloud Compare software, by means of the Scalar Field function, i.e. information that is added to each point of the point cloud, in addition to position and possibly color information. For example, Scalar Fields can be the intensity and number of returns of a Light Detection and Ranging (LiDAR) survey, verticality and flatness values, the origin of the cloud if it is several different dense clouds that are subsequently merged, etc. Thus, by first performing a segmentation of the point cloud in order to isolate only the flooring of the chapel under analysis, a classification was performed on the Scalar Field by setting high color contrast values in order to display the geometries of the different materials in detail. The results of this classification are shown in Figure 3 below.

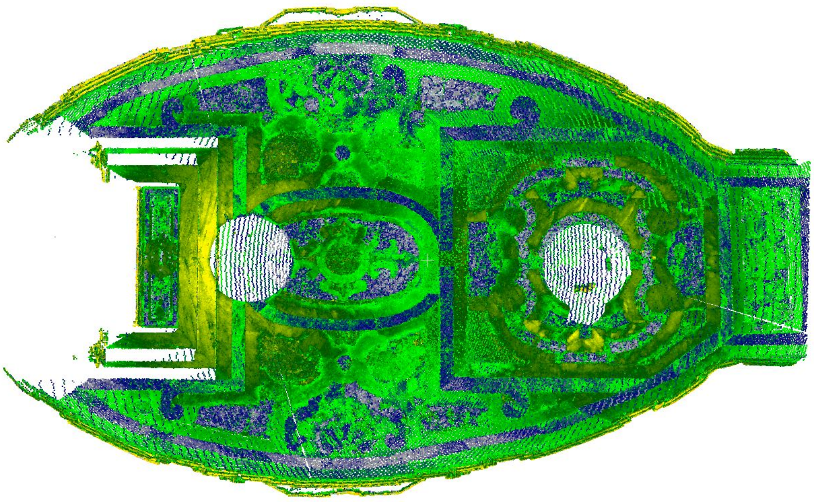

Figure 3: Classification of the point cloud based on reflectance values.

The orthophoto was then exported and imported into the Quantum G.I.S. software (QGIS) v.3.30.2 for the subsequent vectorization and attribute implementation phase (Figure 4).

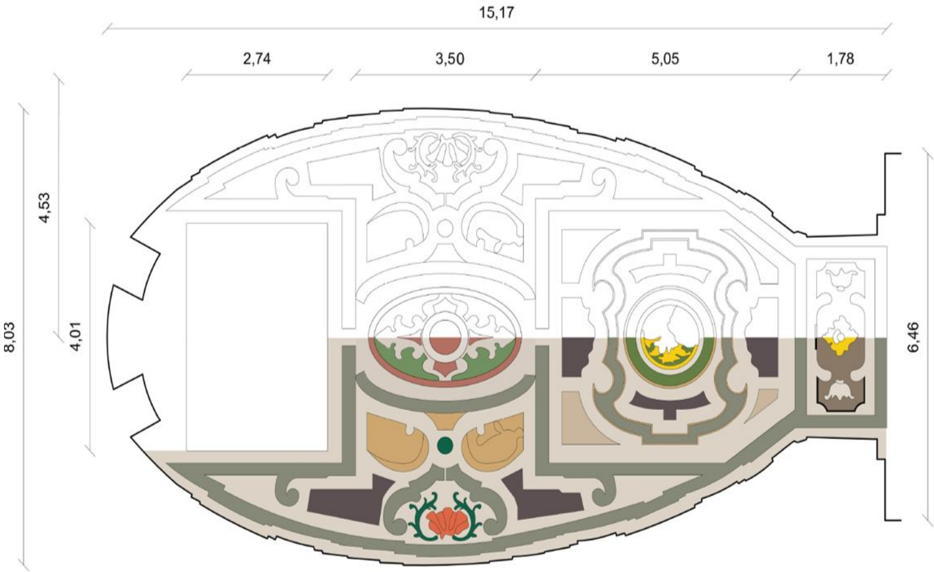

Figure 4: Vectorialization of flooring and marble classification.

3.4. True data

In addition to TLS data acquisition, a photographic documentation was also carried out to analyze in detail the different marbles of which the floor of the church is composed. Therefore, once the orthophotos had been created from the TLS survey, a floor plan was produced that was able to geometrically represent the different areas of each marble. This process was carried out in a G.I.S. environment since, in addition to the geometric information, it is also possible to associate attributes. In fact, using the open-source software QGIS, it was possible to construct a polygon-type shapefile for each marble type in the church. For each marble type, the following attributes were assigned, useful in the study and research phase: common name of marble, petrographic typology, area of the marble portion, macroscopic appearance of marble, period of use, type of use and quarrying.

Figure 5: Overlay of classified data with vectorization.

The polygons were constructed on the basis of a photointerpretation of an orthophoto produced in Cloud Compare software and classified according to reflectance values (Figure 5); therefore, it was possible to obtain the following layout, identifying and classifying the several marbles. This means to create a management and support tool in the field of Cultural Heritage restoration.

4. Results

The tools and commands present in G.I.S. software allowed to associate a relational database with raster or vector content, in the case analyzed an attribute table was implemented to obtain the information described above for each type of material (Figure 6). The previous classification of the data has in fact made it possible to distinguish all the marble elements and to subdivide them into the various inlays; through QGIS query tools it is possible to obtain a series of information not only geometric and petrographic but also historical by clicking directly on the geometric element through the "Identify" command or by carrying out a series of queries. In this way, it was possible to build the statistical analyses concerning the quantity versus the type of each marble (Table 2).

Table 2
Marble types (from a petrographic point of view in Italian language) with respective surface area and percentage of total.

Type	Surface (sqm)	Percentage
Bardiglio	19.29	24.62%
Rosso Levanto	5.05	6.44%
Libeccio brecciated variety	1.47	1.88%
Verde Levanto	1.37	1.75%
Giallo Castronuovo	0.56	0.71%
Libeccio	1.59	2.03%
Verde Calabria	0.66	0.84%
Verde Antico	0.98	1.25%
Occhio di Pavone	4.76	6.07%
Marmo of Carrara	40.7	51.94%
Broccatello	1.35	1.72%
Libeccio (alternating with dark coral breccia)	0.58	0.74%

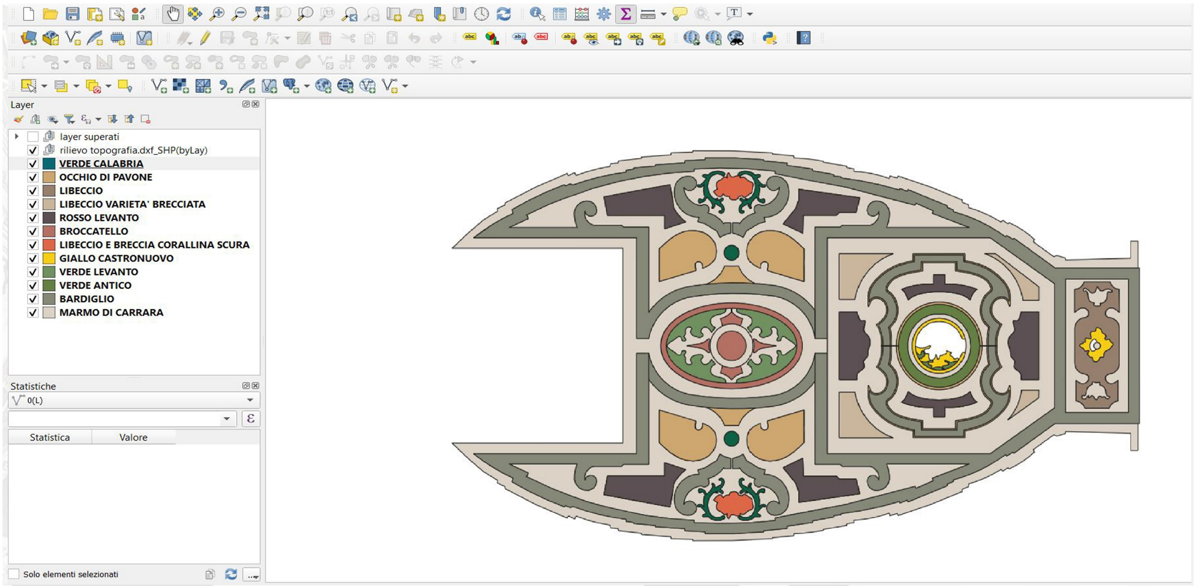

Figure 6: Visualization in QGIS software of the marbles.

In this way, it was possible to realize a management tool in the context of restoration activities. Indeed, through classification and statistical analysis, it is possible to determine the surfaces of the different types of marble and, support restoration activities from a petrographic point of view in order to identify the best compatible materials. Furthermore, through this classification it is possible to analyze the quality of the marbles used and determine the historical-artistic value of the pavement investigated, as well as to hypothesis its date of construction and thus improve the historical and archaeological understanding of the cultural heritage.

5. Conclusions

The Terrestrial Laser Scanning plays a crucial role in digital representation as shown in the case study of the church floor; in fact, it was possible to acquire three-dimensional data with a high level of detail and accuracy, facilitating the creation of accurate digital models. By exploiting the range of signal intensity emitted by the TLS, it was possible to recognize the geometries of the different marble inlays. This data supplemented with photographic documentation improved the classification result. In other words, the TLS data alone made it possible to detect the different geometries automatically (with respect to the reflectance values) but did not allow automatic classification in relation to the different colors of the marbles.

In addition thanks to the G.I.S. tool, it was possible to analyze, represent and interrogate entities or events occurring both on the territory and on architectural realities such as the Chapel of San Cataldo and its conformation. The common operations that can be carried out on databases, such as searches, statistical analyses, graphs, are thus integrated with the functions of a G.I.S. such as the storage of spatial data, their processing and above all their representation in the form of cartograms or tables. The processing of these data in SIS thus makes it possible to visualize and analyze the information in order to research and enrich the data in possession on the marble conformation of the San Cataldo Chapel, but also to plan restoration activities with relative updates over time, thus making it possible to analyze and study the evolution of the architectural identity. Finally, this information can be integrated into other relational databases (RDBMS) in order to increase the sharing of semantic and geometric attributes and improve decision-making processes in maintenance and restoration activities in the field of Cultural Heritage.

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