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Abstract	The case study presented describes the experimentation of 3D digital reconstruction carried out on a portion of the facade of San Michele Basilica in Pavia. The facade is characterized by numerous sandstone bas-reliefs, that have been deteriorating throughout the years, composing narrative cycles of historical kings and myths of the Lombard Kingdom. Starting from acquisitions carried out on the field and through the study of the historical conservation of the decorative tiles, researchers worked to create a digital model representing the actual state of conservation of the *St. George and the Dragon tile*. Such model has been compared to the one based on historical images and surveys carried out during the past century. The goal is to obtain an information system for conservation management protocols and for dissemination of this disappearing heritage. The method applied to the pilot case consists of geometric and material survey, documentation of the state of conservation and analyses with non-invasive techniques, leading to the three-dimensional reconstruction of the tile. The result allows to perceive shapes of the tile that are now illegible and understand the volumes as they should have been. The different conservation status of the tile can be appreciated on the physical object or in virtual mode, through VR system and FDM 3D printing.
Keywords (separated by '-')	Architectural survey - Cultural Heritage digitization - Digital reconstruction - 3D printing - St. George and the Dragon - San Michele Basilica

Digital Reconstruction for the Analysis of Conservation State: The Transmission of Historical Memory of St. George and the Dragon Tile in San Michele Basilica Facade

Elisabetta Doria, Hangjun Fu, and Francesca Picchio

Abstract The case study presented describes the experimentation of 3D digital reconstruction carried out on a portion of the facade of San Michele Basilica in Pavia. The facade is characterized by numerous sandstone bas-reliefs, that have been deteriorating throughout the years, composing narrative cycles of historical kings and myths of the Lombard Kingdom. Starting from acquisitions carried out on the field and through the study of the historical conservation of the decorative tiles, researchers worked to create a digital model representing the actual state of conservation of the *St. George and the Dragon tile*. Such model has been compared to the one based on historical images and surveys carried out during the past century. The goal is to obtain an information system for conservation management protocols and for dissemination of this disappearing heritage. The method applied to the pilot case consists of geometric and material survey, documentation of the state of conservation and analyses with non-invasive techniques, leading to the three-dimensional reconstruction of the tile. The result allows to perceive shapes of the tile that are now illegible and understand the volumes as they should have been. The different conservation status of the tile can be appreciated on the physical object or in virtual mode, through VR system and FDM 3D printing.

Keywords Architectural survey · Cultural Heritage digitization · Digital reconstruction · 3D printing · St. George and the Dragon · San Michele Basilica

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1 Introduction

1.1 State of Art and Case Study

The current research concerns the virtual representations of architectural sites for the transmission of memory for knowledge and conservation of the cultural heritage [14]. The documentation process is developed as a pilot project on a portion of the facade of San Michele Maggiore Basilica in Pavia: the tile of *St. George and the Dragon*, which has an extension of 1.3 × 0.5 m.[1] This tile has been chosen as the pilot case because, starting from the beginning of the twentieth century, it has been the subject of numerous analyses and comparisons, that allow understanding how much the geometry and shape of this bas-relief have changed over time [19]. As analyzed in numerous studies "geometric memory is essential for the knowledge, protection, and conservation of architectural and historical heritage" [3]. Survey and representation via drawings and models introduce heritage conservation actions as tools for protecting the object and its memory [23]. Nowadays, the use of 3D replicas for the preservation practices and analysis of cultural heritage is well established. Physical replicas are perceived as "immediate, surface, temporary, modern, popular, and democratic" [13]. Add to this are immersive fruition and the ways of interacting with the digital data, in the interoperability, and in the possibility of adapting the information to the different communication strategies that the object reconstruction takes shape [25]. The development of three-dimensional digital models allows virtual and physical experiences via 3D printing. In cultural heritage, such technology represents a "challenging domain of application, in relation to the print quality and the low production costs" [29] and the 3D printing of cultural assets allows an immersive tactile experience for users [12]. 3D prints offer opportunities to change experiences for users: the prints can be easily reproduced in multiple replicas and their use is increasingly widespread nowadays [18]. The 3D printing of elements of the Cultural Heritage is nowadays considered one of the possible revolutions in the field of cultural heritage, thanks to its possibility of activating innovative uses in the conservation and communication field [2].

1.2 Historical Background

The Basilica of San Michele is a characteristic example of a Lombard Romanesque gabled basilica and can be dated back to the twelfth century thanks to a vast archive

[1] The research project involves the laboratories DAda- LAB and PLAY of University of Pavia. Project managers are Prof. Marco Morandotti and Prof. Sandro Parrinello. Research group is composed of Dott. Francesca Picchio, Ph.D. Stud. Elisabetta Doria, research fellow and Ph.D. Stud. Hangjun Fu and Ph.D. Stud Silvia La Placa (postproduction vectorial drawings) of University of Pavia.

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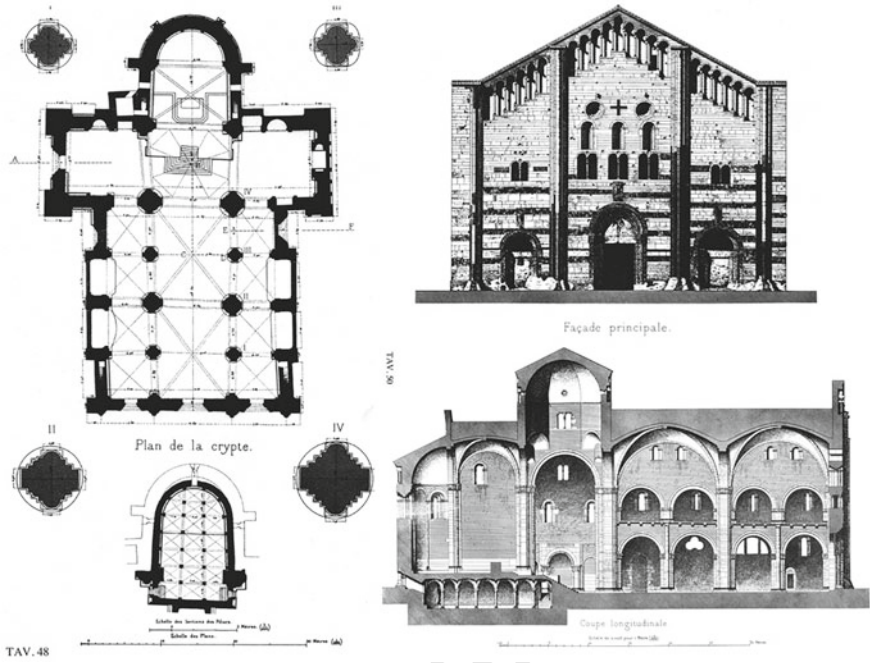

Fig. 1 Historical drawings of the architecture of the Basilica made by F. De Dartein: planimetry, main facade where the tile of the pilot case is present, and longitudinal section [11]

documentation [28]. Archival sources testify the existence of a special throne dedicated to the coronation of sovereigns of the Lombard kingdom during 642–1155 A.D. Within a portion of this timeframe, Pavia remained the administrative capital of the finished kingdom of the Lombard domination [28]. The Basilica has a Latin cross planimetry, with the central body consisting of three naves. Walls are characterized by ashlars of sandstone from the hilly quarries of the Province of Pavia (Fig. 1).

Over the centuries, the Basilica has undergone important partial reconstruction and restoration interventions.[2] Starting from the mid-1900s, Gino Chierici, director of the Superintendence of Medieval and Modern Art in Milan, started a documentation methodology process involving the entire Basilica, via photography and the casting of decorative elements.[3] While the photographic acquisition procedure was carried

[2] An important structural intervention was made in 1489: 4 cross vaults were added, and the side aisles were enlarged. The major restoration works were carried out between 1860 and 1875; Those restorations have a historical-philological aspect and were aimed at restoring the original forms, involving the replacement of mouldings and decorative elements, both internal and external with some copies. Supervision of works has been in succession: Arch. Giovanni Battista Vergani and Eng. Sirio dell'Acqua.

[3] For more details see the SIRBeC PDF file available at: Lombardia Beni Culturali, Pavia. Chiesa di San Michele https://www.lombardiabeniculturali.it/stampe/schede/H0110-12345/. Compiler: Seccareccia, S. (1996). Upgrade: Schiavi, A., Seccareccia, S. [34].

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Fig. 2 Comparison between the current status of conservation of a sandstone decoration (on the right) and its state of conservation in 1942 (on the left) thanks to the photographs of the working group of Prof. Gino Cassinis. The historical photograph (on the right) represents the status prior to the restoration carried out in 1963

out in detail on multiple tiles, casts were never modelled to safeguard the friable decorative stone. Photographic analysis was key for the development of a comparative analysis between the current status and the one surveyed in the mid-twentieth century [10]. Attention to the state of conservation of the facade culminates with a series of intervention proposals starting in 1958. The realization of these proposals took place in 1963 with an assignment entrusted to Piero Sanpaolesi. Following the intervention of Sanpaolesi, in the 70 s campaigns began to investigate the state of conservation of the stones of the Basilica, which had not undergone interventions after those of 1963 (Fig. 2).

The treatment carried out by Sanpaolesi[4] slowed the degradation process but with an unsatisfactory final effect at medium distance, as highlighted by studies conducted in the 1970s [19]. The products chosen for the intervention as well as the lack of routine maintenance led to the detachment of flakes of various sizes.[5]

[4] Piero Sanpaolesi (1904–1980) was an engineer, architect, restorer, architectural historian, and Italian academic. Protagonist of restoration culture of the second half of twentieth century, he was among the first to experiment with methods for the consolidation of stone materials used in architecture. See in references: Piero Sanpaolesi digital Archives University of Florence.

[5] For more information and technical references related to the conservation intervention and its criticisms see: Lombardini N. in *I restauri della facciata della Basilica di San Michele Maggiore a Pavia* (2018), pp. 68–72.

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Fig. 3 Position of the *St. Geroge and the Dragon tile* with respect to the Basilica facade

Due to the aforementioned degradations, surveys and monitoring of the state of conservation activities were carried out. Gino Cassinis, full professor of topography at the Politecnico di Milano, made the photogrammetric survey of the most deteriorated bas-relief of the facade, identified with St. George and the Dragon [19]. The state of high deterioration of the stone surface after the 1963 intervention is evident from the comparison with historical drawings of the late nineteenth century by Fernand De Dartein, and photographic images were taken before and after the restoration, from the early twentieth century and in the 1970s [11]. Surveyed data has been used to produce comparative models aimed at the reconstructive analyses, allowing for the digital modeling and virtual reconstruction of *St. George and the Dragon tile* in its original state of conservation before the 1963 restoration interventions. The facade of San Michele Basilica is characterized by several bas-reliefs creating a decorative story and preserving the glorious past of the city and its territory. *St. George and the Dragon tile,* positioned in the facade next to the central portal at a height of 2.5 m, is one of the most degraded and compromised. For this pilot case, three-dimensional modeling and historical reconstruction analysis were conducted to build a proposal for the valorisation of the cultural heritage and the development of a management system for conservation and an immersive virtual reality system (Fig. 3).[6]

[6] The geometric and material survey of the external walls of the Basilica is part of two consulting contracts as a research activity aimed at digital documentation and advanced vector representation: South external wall and roof survey stipulated between the Department DICAr of the University of Pavia and the company REA – Restauro e Arte S.r.l., Facade survey stipulated between the DICAr Department of the University of Pavia e Superintendence of Archeology, Fine Arts and Landscape for the provinces of Como, Lecco, Monza Brianza, Pavia, Sondrio, Varese (Functional area of architectural heritage).

2 Project Development Methods

2.1 Survey and Acquisitions of Data

The tile of *St. George and the Dragon* has been analysed since the 1940s[7] with state-of-the-art photogrammetry techniques.[8] Thanks to historical drawings, photographs, and studies conducted throughout the 1900s, this tile is the ideal case for experimenting with historical modeling and detailed documentation. The oldest reference to the state of conservation of this tile is due to Fernand De Dartein, who represented in detail numerous bas-reliefs of the Basilica in his work "*Etude sur l'architecture lombarde*" [11]. Starting from 2020, the DAda-LAB and PLAY laboratories of the University of Pavia started a documentation campaign on the external perimeter and on the facade of the Basilica, focusing on *St. George and the Dragon tile*.

Different digital tools have been used and integrated with the acquisition campaign: TLS laser instrumentation (Faro CAM2 S150), SfM photogrammetric techniques with UAVs and reflex cameras (DJI Mavic Mini, DJI RTK, Nikon D850/24–70), and Artec Eva 3D scanner for metric acquisitions of the tile.[9] The Artec Eva 3D scanner uses a close scanning technology (range 50–70 cm) with structured light pulses provides, in the scope of this project, an optimal mesh detail to acquisition time ratio. Acquisitions have to be performed at a close distance, using ladders for the raised position of the analysed object. The survey phase, involving the structured light laser Artec Eva, was conducted on the field by acquiring 4 separate scans, subsequently merged in post-production using Artec Studio software by Artec3D.[10] To facilitate the integration between laser and photogrammetric acquisition, six black, and white targets were positioned around the tile, to be captured by all the instruments involved (TLS, MLS, Artec Eva and cameras) enabling reliability checks through the registration different point clouds and mesh models (Figs. 4 and 5).

[7] Convention for the Safeguarding of the UNESCO Intangible Cultural Heritage, 2006: adds the enhancement of intangible values to the Franceschini Convention for the Safeguarding of Cultural Heritage of 1967.

[8] The photogrammetric acquisition saw the detection of 500 points in a time of one hour. See: Lombardi, 2018, pp. 39.

[9] The research was enforced in the collaboration "Agreement for the development of research activities about the digital documentation of cultural heritage and landscape using drones" between DICAr Department of Civil Engineering and Architecture of University of Pavia and iFlight Technology Company Limited, signed in February 2020, lasting three years.

[10] The Artec Eva is a handheld, colour scanner released in 2012, that can capture and process up to two million points per second. The scanner was designed for the capture of medium to large objects, as the tile case study. The device has a scan area of 214 × 148 mm at its closest range and 536 × 371 mm at its furthest, a 3D resolution of up to 0.5 mm, and a 3D point accuracy of 0.1 mm. Eva can operate at distances between 0.4 m and 1 m from the object, capturing up to 16 frames per second. Data can be exported as a mesh model in a.obj file. For more information see: Evers, P.: Eva 3D Scanner delivers accurate colour and structure data without markers, In: 3ders website, Archived from *the original* on 5 May 2016.

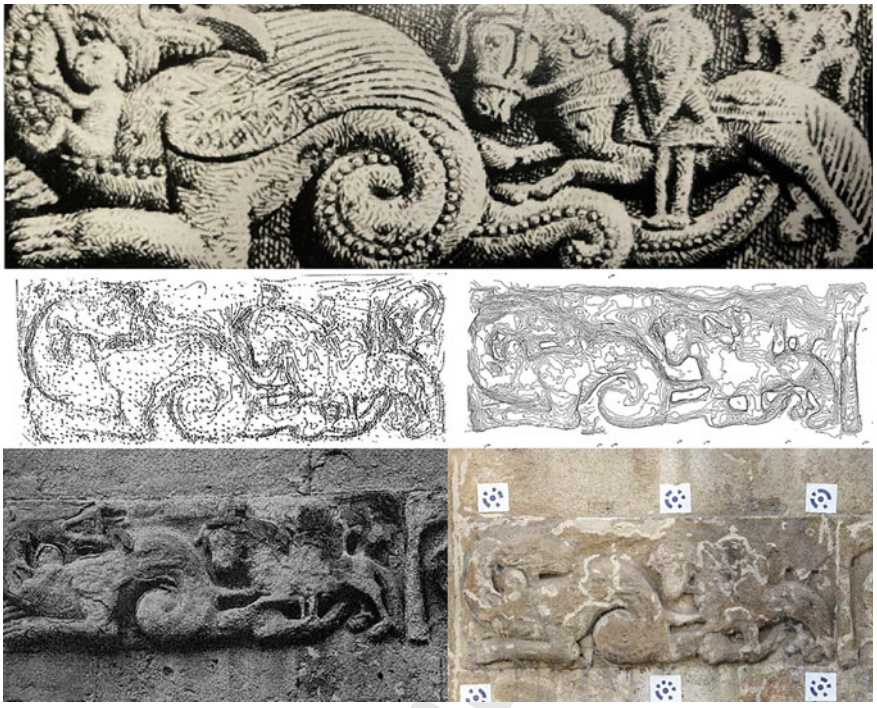

Fig. 4 *St. George and the Dragon tile.* Above: the historical drawing by F. De Dartein [11]. Centre: Images of the studies conducted by G. Cassinis: topographic points (center left) and isolines (center right). Below: comparison between the mid-1900s photo (left) and the current (right) highlights the severely altered state of conservation

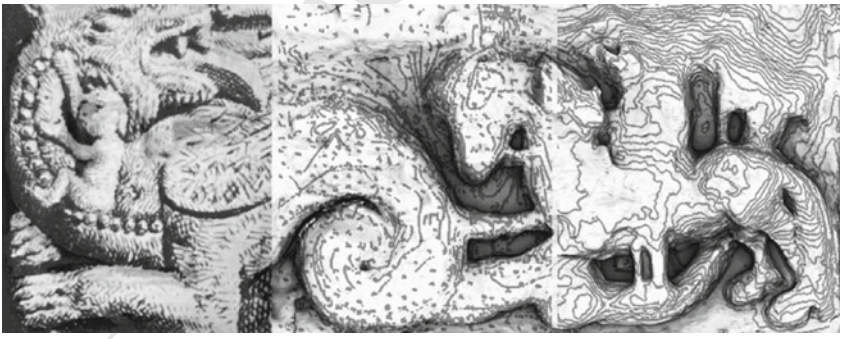

Fig. 5 Comparison between the archive sources used to develop the historical reconstruction model. From left to right: drawing by F. De Dartein, [11], topographic points and isolines curves developed by prof. Gino Cassinis. For more details about the work conducted by Cassinis, see: Cassinis, G.: *Riproduzione di un bassorilievo con procedimenti fotogrammetrici.* In: Palladio, a. 6, n. 5–6. C. Colombo, Roma, 1942

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Fig. 6 Survey phase conducted with the 3D Artec EVA via structured light on the pilot case of *St. George and the Dragon tile*. On the right: data post-production phase. Above are visible the 4 different scans acquired, highlighted in different colours. On the lower part, the final model obtained via scans merging

Following the registration of the four Artec Eva scans, a global mesh model was developed with the application of the texture. The final digital object is a textured, open mesh 3D model in which the level of metrical and geometrical accuracy has been validated with the laser scanner point cloud (Fig. 6).

2.2 Virtual and Physical 3D Reconstructions

The three-dimensional model obtained with the Artec Eva scanner represents the digital copy of the tile in the current state of conservation [32]. The project is aimed

at preserving an architectural artifact of such artistic relevance, at the activation of museumization and protection processes as well as the enhancement of cultural heritage [6]. The digital reconstruction of the tile in a past state, based on historical archive sources, was used to feed immersive virtual reality systems. Starting from the current state of conservation, via additive techniques, the backward process from the eroded object to the original shape was rebuilt via ZBrush, a digital sculpting software.

The default ZBrush sculpting tool, without modifiers or custom settings, displaces outwards the vertices over which it passes, simulating the addition of clay to a sculpture. Different effects and additions can be achieved with various brush modifiers, such as Strokes, Alphas, and edit curves [36]. The sculpting process was carried out by adding material from the model of the current status, using the drawing by De Dartein as a reference. The drawing was sized on the digital survey thanks to notable points that are still visible nowadays and used as a basis for 2D geometries (Fig. 7).

The third dimension was interpreted thanks to the oldest available isolines survey and topographic points, representing an intermediate state of conservation between the De Dartein drawings and the current image of the tile. Multiple aspects of the original documents were considered during the reconstruction phase. For example the intensity of the shadows visible in the historical images, useful to understand the high of the bas-relief geometries; the trend of isolines curves and of acquired points by Cassinis and Bezoari, useful to understand the differences in-depth, the comparison with the historical drawing of De Dartein, acting as a reference for the sculpturing process of the reconstructive model [19]. The digital model representing the actual image of the tile was transformed into a solid closed mesh model and then exported to proceed with the digital reconstruction [30]. The next phase of both

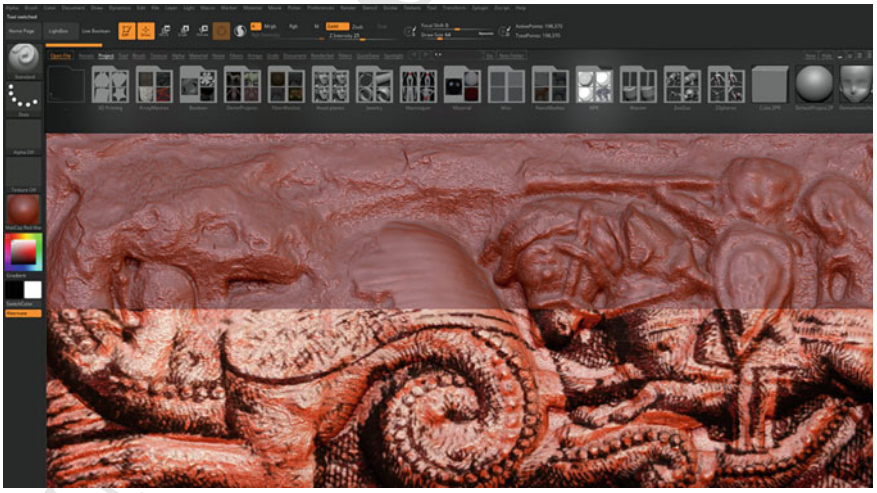

Fig. 7 Image representing the sculpting phase using ZBrush. Above: material addition phase. Below: overlap with the drawing by F. De Dartein

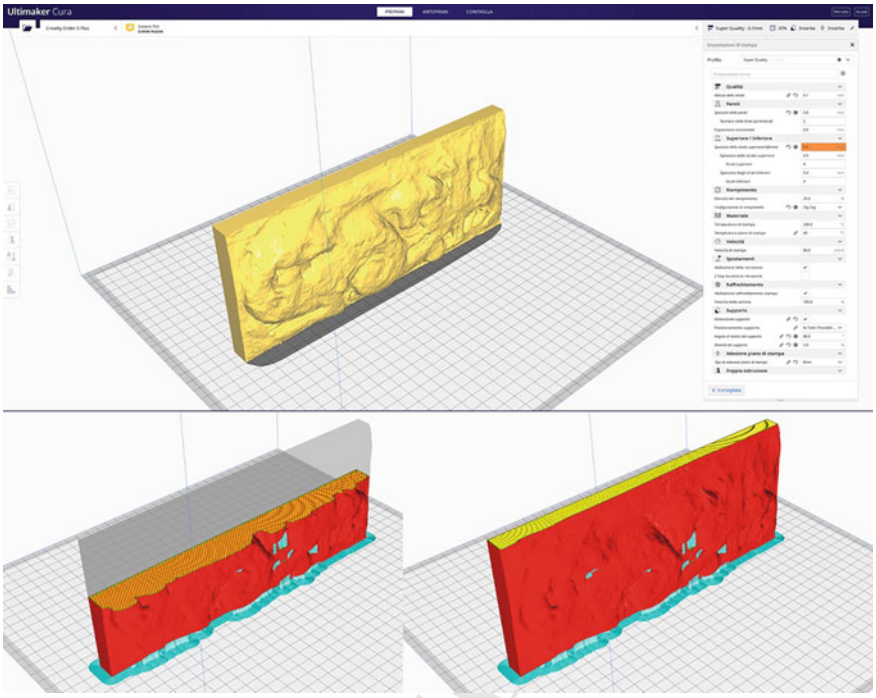

Fig. 8 Management of the 3D printing phase of the tile. The model was printed along the z axis, leveraging the properties of the printer, since such axis grants highest possible detail with a 0.4 mm extruder. In the images below: progress of the printing phase by levels with the parts added to adhere to the base and the supports for the decorations, highlighted in blue

the enhancement of the current state and the historical reconstruction consists of the physical transposition of the digital models. The physical construction makes the tile an object that can be experienced from a tactile point of view, making the knowledge of its shape accessible to different categories of users and with different informative purposes (Fig. 8).

The 3D printing of the two models, the current state of conservation and historical reconstruction, was made using FDM fused deposition printing with Ender 5-plus printer. The details of the models allow a 1:1 scale print reproducing exactly the real dimensions of the decoration. The tile printed as a test for the calibration of the instruments was made on a 1:5 scale. Further experimentations were performed to test the feel of the printed material to the touch and to reproduce the material effect of the original bas-relief. The negative cast of the contemporary *St. George and the Dragon tile* was printed to create a plaster and a cement model to simulate the graininess and friability of the real stone (Figs. 9 and 10).

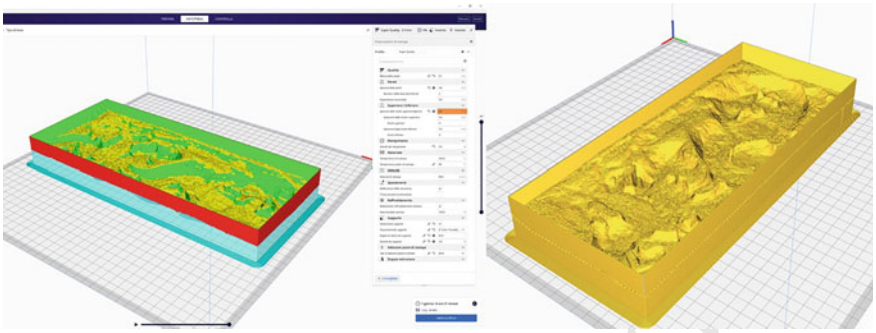

Fig. 9 Design of the 3D printing of the tile to produce a concrete and plaster cast

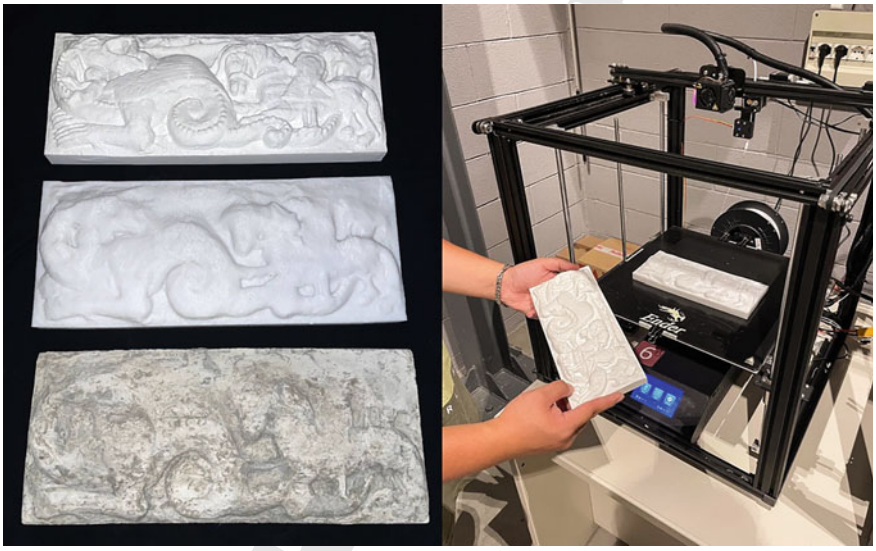

Fig. 10 On the left, from top to bottom: Tile reconstructed in PLA filament, tile in the current state of conservation in PLA filament, concrete tile in its current state of conservation. For the PLA prints, two filaments with different colours were used to test the visual rendering of the material. The concrete tile was produced with a 3D-printed cast. Concrete was tested with inert of different sizes to find the solution that was closest to the real material effect. Although the current tile is clearly visible to anyone who goes to the Basilica, the position in which it is located does not allow direct observation. This is possible with a three-dimensional physical reproduction which can be printed on a 1: 1 scale

2.3 Usability and Potential of the Digital Three-Dimensional Reconstruction

The sculpting process allows representing different states of conservation. The historical phases enable a visual timeline of the historical evolution, accelerations, and stabilizations of visible surface decay and pathologies, linking such alterations to the restoration and interventions as well as to the passage of time. The heritage dataset can be used to structure an information system for documentation, conservation, and enhancement planning. Digitization becomes the interpretation or transposition of an architectural or decorative heritage value over time, acting as a representative form of physical memory [14] and, in its perceived identity form, a symbol of collective memory. The transmission of memory, despite being intangible, is one of the purposes of digitization of built heritage, enhancing the aspects of both the physical conservation of the asset and its strength as an identifying element for the community (Fig. 11).

The enhancement of non-material aspects of the asset allows the development of conscious management of the object, to define the asset itself as "valued" [23]. Valorisation of built cultural heritage is connected to the policies and practices of use and preservation. Despite being a possible goal for the process of conservation, the valorisation phase can also represent a set of actions organized and coordinated

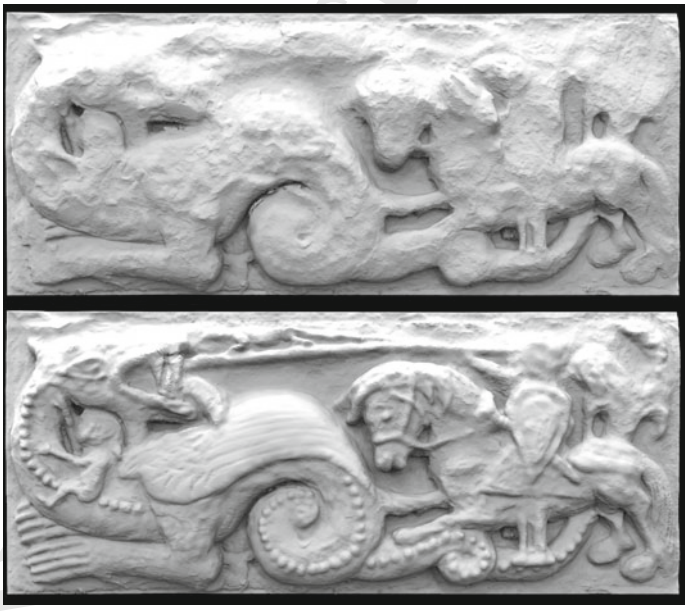

Fig. 11 Rendering of digital models that can be used as a basis for the dissemination and usability of the cultural product. Models can be easily inserted into immersive or orbiting reality platforms that can be connected to websites and tourist web portals [32]

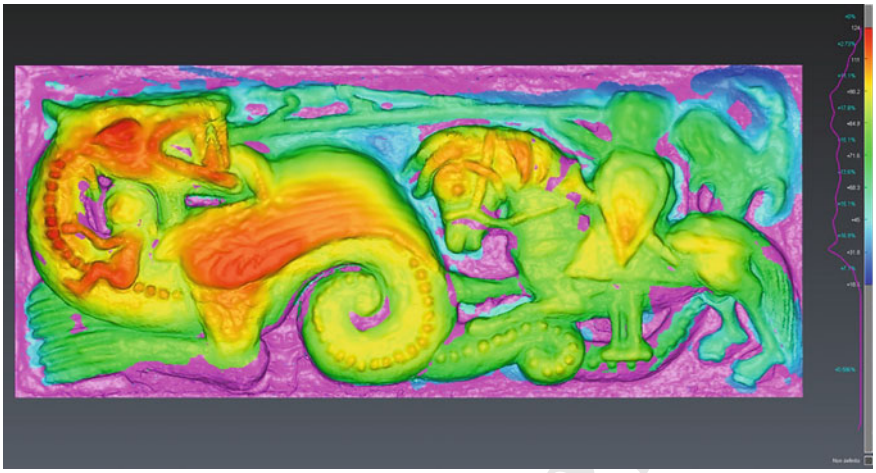

Fig. 12 Comparison between the two states of conservation of the superimposed tiles. The current state of conservation is coloured in pink and is visible only where no further disintegration is present. The reconstructed tile thickness (from blue to red) was mapped with progressive colours. Cooler colours indicate where it has been least rebuilt, while warmer colours indicate protruding points with more rebuilding. Thanks to this process are possible to evaluate the amount of eroded material and the relationship between time and material loss

in time (intervention time schedule), aimed at increasing the quality and identity of the individual heritage [16] (Fig. 12).

3D scanning tools and advanced modeling programs have encouraged studies on modeling as instruments for visualizing, designing, and enhancing new methods of analysis within the field of architectural heritage [8]. Documentation and valorisation can be performed through digital 3D models enriched with metadata, broadening to scope both for informative system level and specific technical level uses. Digital technologies applied to cultural heritage are the platforms in which models and metadata can be linked in interoperable and interactive formats [7]. In the field of Cultural Heritage, such technologies include 3D models and GIS data visualizers [4]. For this specific case, experimentation began to integrate into an ArcSCENE platform a mesh model of the facade of the Basilica with a simplified representation of the decorations and overlapping the selectable surface of the tile.

All mesh models are exported from the modeling software in their respective format (.rsh,.obj) are imported in ArcSCENE as shapefiles. Textual data related to the tile can be entered through the upload of excel files, as images or pdf through hyperlinks (see Fig. 13). The information system is still in early development, with CIDOC-CRM compatibility being targeted among future developments. Nowadays the information system contains the tile of *St. George and the Dragon* with associated photographs, links to the models, images of comparison between the models, information related to the dates of restorations and interventions carried out; the

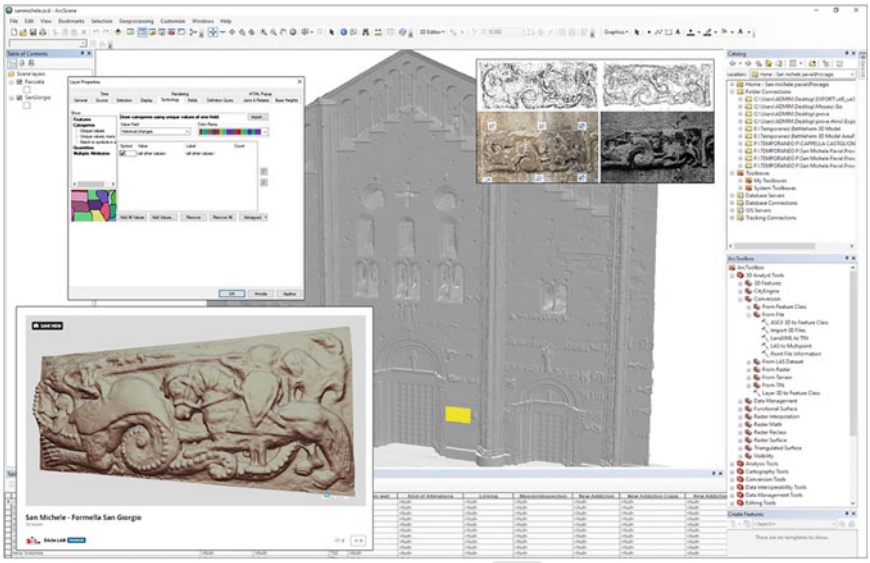

Fig. 13 The inclusion of the models in the georeferenced information system is one of the possible approaches for the planning of conservation operations. Once the tile model (in yellow) has been inserted into the reference system, it is possible to link metadata to the model. In this case study metadata refers to historical, technological, and material information acquired. Additional data, such as historical and current photographs, pdfs, and links are connected as pop-up hyperlinks

reconstructed model link is available online.[11] With the increase of a large number in the tile dataset, it will be possible to create thematic maps via queries insisting on the dataset (Fig. 14).

3 Conclusion

The process conducted on the pilot case follows the documentation of different states of conservation and their three-dimensional reconstruction via non-invasive techniques, suitable for friable and non-cohesive materials. The dataset acquired and post-produced during the experimentation phase represents a case study to structure the documentation and enhancement protocols of the decorative surfaces and elements of the Basilica external fronts. The goal is to be able to proceed with the historical reconstruction for several other tiles and decorations to have a digital and three-dimensional archive of the friable decorations. An information system for data

[11] It is possible to view the model of the tile reconstructed on historical data at the following link: Dada LAB: 3D digital model, the reconstruction of the ancient tile on the facade of Sab Michele in Pavia on Skecthfab: https://skfb.ly/6XPEB [31].

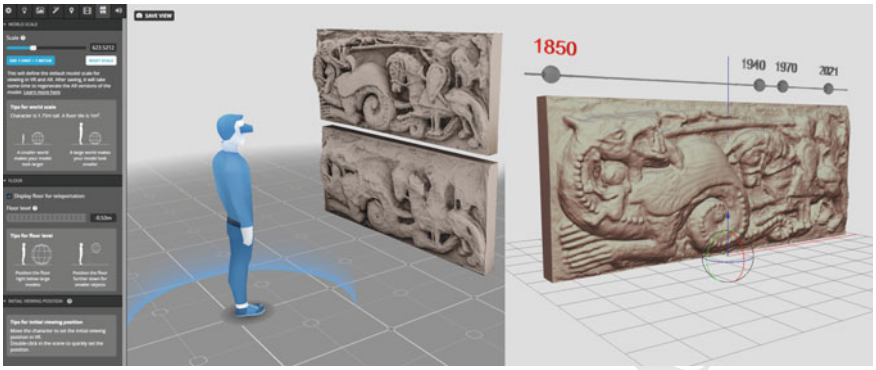

Fig. 14 Positioning of the three-dimensional model of the tile in a virtual environment for immersive reality aimed at the usability of the decorative object and at knowledge sharing. It is possible to view the digital model online [32]

integration was designed and built within the aim of this pilot case, as a single information platform for combined data analysis across multiple sources. Information systems, allowing for the integration, entry, and update of data, allow the development of analyses to monitor the state of conservation over time and guarantee an updatable archive of the asset and management protocols. The historical progress of the conditions of the tiles can also be used to share knowledge of the heritage, including models in usability platforms to improve the virtual musealization of the Basilica and its possible application in the information-tourism field. The 3D models shown in this contribution were created to develop the perception of cultural heritage and decorations no longer existing and no longer completely visible and appreciable nowadays, both via virtual representation in information systems and with physical artifacts.

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