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An operational workflow for documenting and communicating architectural heritage: from survey to 3D printing

Digital surveying and rapid prototyping techniques are important tools to support processes related to cultural and architectural heritage. Digital surveying can be used to document, analyse, and enjoy the built heritage thanks to point clouds and detailed digital models resulting from the processing of data acquired during field activities. 3D printing, on the other hand, enables the creation of realistic physical replicas of heritage artefacts that can support activities related to analysis, documentation, conservation, valorisation and enjoyment. The use and combination of these techniques to architectural and cultural heritage have brought benefits and advantages since digital and physical replicas can be used in the processes of documenting, analysing, preserving and enhancing historical artefacts by promoting their accessibility on multiple levels.
The paper discusses the results of research aimed at defining and testing an effective workflow for the development of physical models suitable for the analysis, documentation and communication of architectural heritage. The experimentation was performed considering as a case study a peculiar element of architecture, a historical portal. The paper illustrates the technical challenges faced starting from the photogrammetric survey to the digital reconstruction of the analysed artefact for 3D printing, with a focus on the printing parameter settings used to produce physical replicas with high-quality, but different resolutions and scales, to be used for several purposes, such as analysis and documentation and education and communication.

Keywords:
Photogrammetric survey; 3D modelling; 3D printing; Phigital Heritage; Knowledge and documentation of architectural heritage

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INTRODUCTION

The three-dimensional model of architecture, intended as a scale representation of an artefact, has always been a valuable tool for representing and communicating an architectural project (Fu, 2023). The physical model can explicate architectural forms and complex geometries; therefore, it has become a tool for studying and analysing a project since it can describe the object in its whole or significant parts (Fu, 2023).

The development of digital technologies and experiments in the field of cultural heritage have made it possible to define operational procedures for data acquisition and processing from which digital models of artefacts are derived. These models are a reliable representation of artefacts (Brusaporci, 2017) and can be used not only for knowledge dissemination and information sharing but also for study and critical or interpretative analysis (Balzani, 2017; Marra 2023a). From these digital replicas, it becomes possible to produce the corresponding physical models by using 3D printing. Rapid prototyping exploits additive manufacturing techniques to create physical replicas of objects with complex architectural or geometric shapes. 3D printing is now widely used for realising replicas to be exhibited within museum collections to promote the conservation, enhancement and accessibility of cultural heritage (Russo & Senatore, 2022; Kantaros, Soulis, & Alysandratou, 2023; Marra, 2023b). Such physical replicas are also an interesting tool for heritage knowledge and documentation because their accuracy and the possibility of making multiple copies in a relatively short time allows for carrying out analyses and simulations of possible interventions that could be realised on the real object.

The present study is part of this framework and is aimed at identifying an efficient workflow for producing physical prototypes useful for analysing and documenting historic buildings. In particular, after acquiring the artefact's morphological and dimensional information through image-based survey techniques, two different procedures are proposed for making physical replicas (Fig. 1). The first proposed procedure involved the realisation of the prototype starting from the appropriately edited model returned by the digital photogrammetry process. In the second procedure, on the other hand, the 3D print of the artefact was obtained from a three-dimensional model made through a manual modelling procedure following the critical analysis of the information collected in the survey phase.

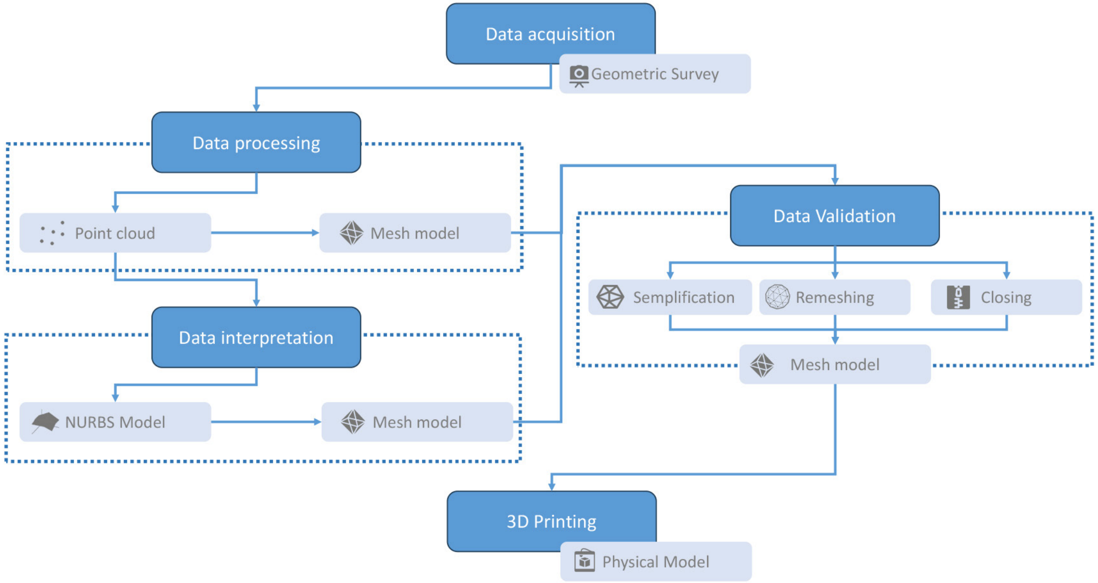
The experimentation was carried out on a peculiar element of historical architecture, the portal, to evaluate the proposed procedures and the quality of the physical models obtained in relation to the goals of heritage knowledge and documentation.

STATE OF THE ART

In recent years, digital survey techniques and 3D printing have changed the approaches to cultural heritage. In particular, knowledge and documentation processes have benefited from the digital tools in 3D surveying. The techniques currently available allow to obtain point clouds with a high level of detail and accuracy that can be used for different purposes (Picchio, Parrinello, & Barba, 2022; Gil-Piqueras, & Rodríguez-Navarro, 2023).

Several investigations have been carried out on digital photogrammetry, both terrestrial and aerial, which have led to defining rigorous operational procedures for data acquisition and restitution, demonstrating the reliability of this technique (Altman, Xiao, & Grayson, 2017; Elkhrachy, 2022). Thanks to digital photogrammetry, it is possible to acquire a large amount of data and to return, in a short time, both a three-dimensional mesh model and two-dimensional data, such as photoplans, of the artefacts under investigation. The image-based survey techniques' results are metrically reliable

Fig. 1 - Flowchart of the procedure.



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and consistent with the formal, geometric and chromatic aspects of analysed architectures. Therefore, these outputs can support, on several levels, the documentation activities underlying the conservation, valorisation, and management processes of the cultural heritage (Barba et al., 2019; Ulvi, 2023; Calisi, Botta, & Cannata, 2023; Torres-González, Cabrera Revuelta, & Calero-Castillo, 2023).

The application of digital techniques to the built heritage and the high level of detail of the models resulting from these processes, together with the development of rapid prototyping techniques, has pushed research towards the creation of physical copies of complex objects with a high degree of precision and at a relatively low cost (Balletti, Ballarin, & Guerra, 2017; Kantaros, Ganetsos, & Petrescu, 2023). There are different technologies in the field of 3D printing, such as material extrusion (Fused Deposition Modelling - FDM/Fused Filament Fabrication - FFF), vat photopolymerization (Stereolithography - SLA), or powder bed fusion (Selective Laser Synthesis - SLS), which produce physical replicas in different materials from the digital model (Inzerillo, & Di Paola, 2017; Kantaros, Ganetsos, & Petrescu, 2023). The physical 3D model obtained from the printing process can reveal the complex geometric shapes of architecture. It also represents valuable support for developing detailed analyses and identifying innovative and alternative solutions for artefact conservation and restoration (Bonora et al. 2021; Parfenov et al., 2022).

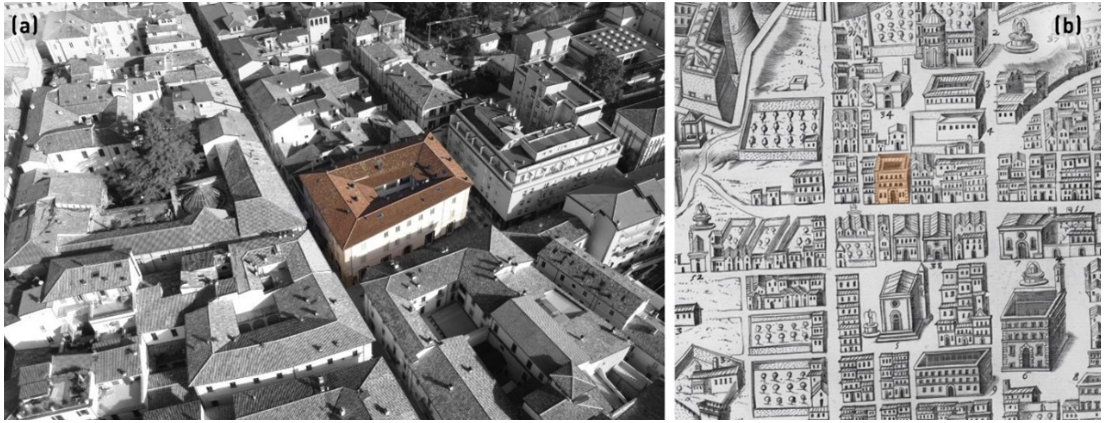
3D printing also plays a significant role in the cultural heritage communication and valorisation processes. Several studies in the literature point out the valuable role of physical prototypes, also integrated with different techniques and solutions, in the field of cultural heritage valorisation and communication of museum collections (Fatta, & Fishnaller, 2018; Fergonese et al., 2019). In addition, physical prototypes obtained by 3D printing have the potential to remove barriers that hinder accessibility to heritage by people with physical and/or sensory disabilities (Candito, & Meloni, 2022). In this framework, the research carried out is numerous and proposes different operational procedures applied both to the artefacts exhibited in museums and to the architecture and its details (Scianna, & Di Filippo, 2019; Sdegno, & Riavis, 2020; Gonizzi Barsanti, & Rossi, 2022; Kantaros, Soulis, & Alysandratou, 2023; Marra, Vespasiano & Brusaporci, 2023).

THE CASE STUDY: THE PORTAL OF PALAZZO QUINZI

The portal under study is located in the historic centre of L'Aquila, more specifically is the main portal of Palazzo Quinzi (Colapietra, 1978, pp. 468-469), also known as Palazzo Di Paola, at the intersection of Corso Vittorio Emanuele II and Via Giuseppe Verdi (Moretti, & Dander, 1974, pp.172-173). This building has an almost square floor plan, characterized by a trapezoidal courtyard. The peculiarity of this geometry, not really diffuse in the context of the historical centre, is probably due to pre-existing buildings (Zordan, 1992, p.88). The three free fronts have a clear horizontal and vertical scan made by the alignment of the holes on the three levels, from the cornices and from the crowning, but above all by the mighty rusticated cantonals that articulate the corners. On the main front, the portal, which shares the design of the ashlars with the cantonals, highlights the central axis of access to the courtyard.

Although, as mentioned, Palazzo Quinzi has traces of pre-existing buildings, and inevitably some partial transformations after the XVI century, its overall image is probably one of the clearest testimonies of the palace architecture of L'Aquila in the second half of the '500. After a gradual abandon the model of the Tuscan palace, which influences the architectural production from the middle of the '400 (Centofanti, & Brusaporci, 2011, p.165), the city opens to roman influences, in particular to the Mannerist re-elaboration of the school of Bramante (Centofanti, & Colapietra, 2009, p. 47-49). The decisive case is that of the palace of Margaret of Austria (Centofanti, 2010), followed by the Palazzo Carli all'Annunziata (Centofanti, Brusaporci, & Vespasiano, 2019) and precisely from the Palazzo Quinzi. These three buildings stand out with the highlighting of rusticated cantonals, in the representation of the city designed by Ieronimo Pico Fonticulano and engraved in Rome by Jacopo Lauro in 1600 (Clementi, & Piroddi, 1986, p.98) (Fig. 2).

Fig. 2 – Palazzo Quinzi in the historical centre of L'Aquila: (a) An aerial view of the building (the only one in colour); (b) a detail of the plan of the city of L'Aquila, engraved by Jacopo Lauro in Rome in 1600, from a drawing by Ieronimo Pico Fonticulano, emphasized in orange at the centre Palazzo Quinzi. Although the level of detail of the design is not very high, it is possible to recognize the rusticated cantonals and the portal ashlars. The same elements can be identified in the palace of Margaret of Austria (nr.6) in the lower right corner.



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The portal (Fig. 3) has a vaulted hole with a rusticated frame, enriched by two ashlar pilasters, included in a smooth stone background field. The rustication continues in the ring of the arch, in which the smooth and quadrangular key is distinguished from the other pentagonal ashlars, domed, and characterized like the others by an ornamentation of geometric rustic scratches. At the base of the arch, two moulded shelves go into retreat rather than protruding from the profile of the frame. The pilasters are concluded by capitals simply moulded, and their design continues in the background field outwards and inwards in the field between the pilasters and the rusticated ring of the archivolt. A high and projecting moulded frame crowns the portal, forming a balcony on the first floor.
In terms of geometric composition and plastic articulation, the portal could recall some drawings of rustic portals by Sebastiano Serlio, in the book "Extraordinario" of the Seven Books of Architecture (Serlio, 1558, c. 7r). The use of this book as a reference in architectural orders is documented in L'Aquila at the end of the XVI century (Colapietra, 1978, p.435).

Fig. 3 – The portal of Palazzo Quinzi.

Fig. 4 – The elaboration of the photogrammetric model: (a) the sparse cloud; (b) the dense cloud; (c) the texturized mesh; (d) the model ready for the export in .stl format and the importation in the slicer software.

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PHOTOGRAMMETRIC SURVEY AND MESH MODEL

With the aim of obtaining information on the morphological and dimensional characteristics of the portal under study, a photogrammetric survey campaign was conducted, which allowed the acquisition of relevant data for the knowledge and documentation of the artifact but also for the realization of different physical prototypes.

The photogrammetric survey was made with a reflex camera (Canon Eos 1200D). In total 114 shots were taken (5184x3456 px) at distances varying between 1.5 and 4.5 m. Considering the small size of the architectural element and the substantial absence of undercuts or portions of the artifact poorly visible from the ground it was considered not necessary to use a drone to obtain images from above. The dataset thus obtained was processed with the Agisoft Metashape software, obtaining a sparse cloud consisting of 677K pt, reduced to 191K as a result of filtering operations and the elimination of reconstructed but not of interest portions of the building (Fig. 4a). On this basis, the dense cloud, consisting of 18 M pt was created, with a processing time of 6h50' (Fig. 4b). The dense cloud was exported in .e57 format and used as the basis for NURBS modelling, detailed in the next paragraph. Remaining instead within the Metashape software the dense cloud was used as a basis for the realization of the mesh, consisting of 1 M faces and 558K vertices, with a processing time of 30' (Fig. 4c). This mesh, exported in .obj format, was imported into Rhinoceros to proceed with the implementation of the .stl model. This step was necessary because the mesh obtained by the photogrammetric process is limited to the external surface of the artefact; therefore, it is presented as an open surface and not as a volume, a necessary condition for it to be correctly interpreted by the slicing software and consequently 3D printed. Therefore, flat surfaces have been added to delimit horizontally and vertically the volume to be printed (Fig. 4d). The mesh elaborated in Metashape also included a portion of the paving in front of the portal, which was considered not to be eliminated at this stage and constitutes the only macroscopic difference with the NURBS model. Another operation carried out in the modelling environment was to eliminate the two handles on the doors of the portal, which had not been correctly reconstructed and had given rise to artefacts. The resulting model was exported in .stl format, ready for import into the slicing software.

THE NURBS MODEL: FROM SURVEY TO CRITICAL RESTITUTION

The point cloud derived from the photogrammetric survey process represented the starting point for creating a digital replica of the analysed portal through a free-form surface modelling software. This replica is the result of a critical analysis process of all the geometric, dimensional, and typological information acquired during the survey campaign (Savini, Fabbrocino & Marra, 2021).

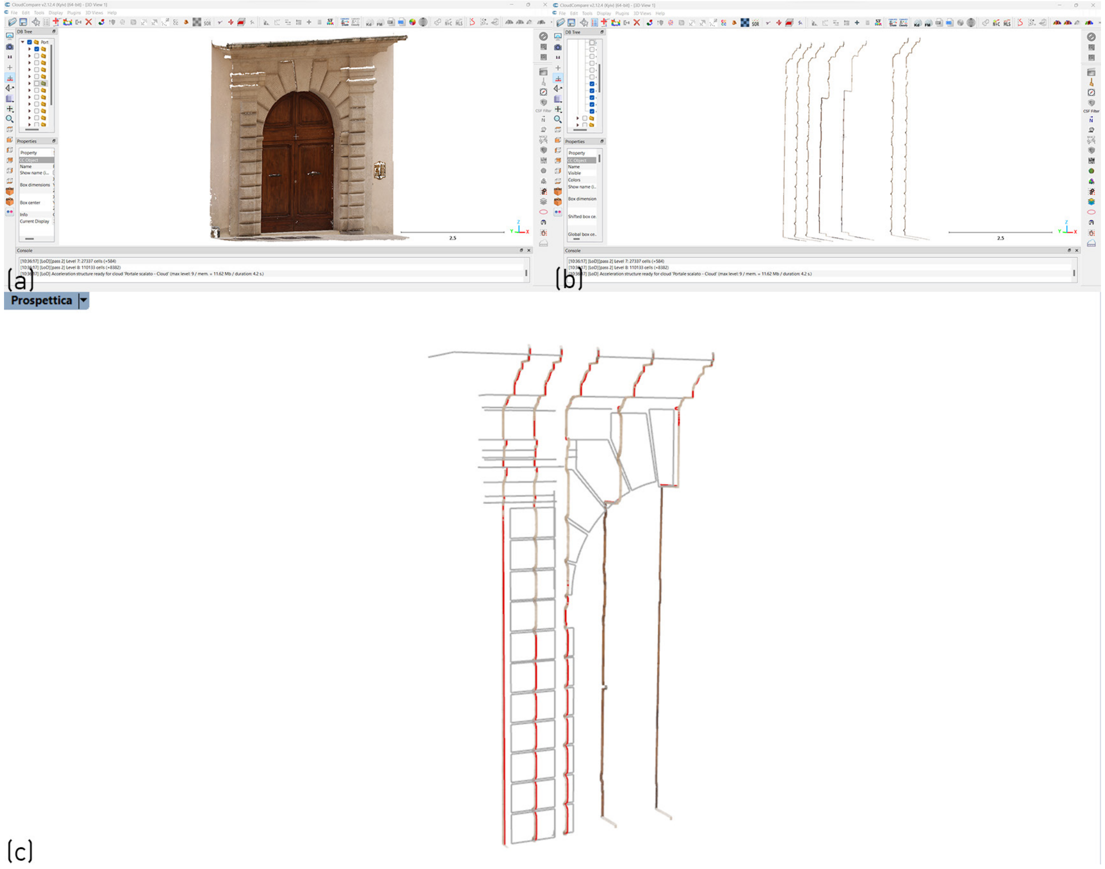

Fig. 5 – Integration of different software for the development of the NURBS model: (a) point cloud from Photogrammetry imported into CC; (b) slices of the point cloud; (c) import into modelling software and development of generatrix (red) and rails (grey) curves.

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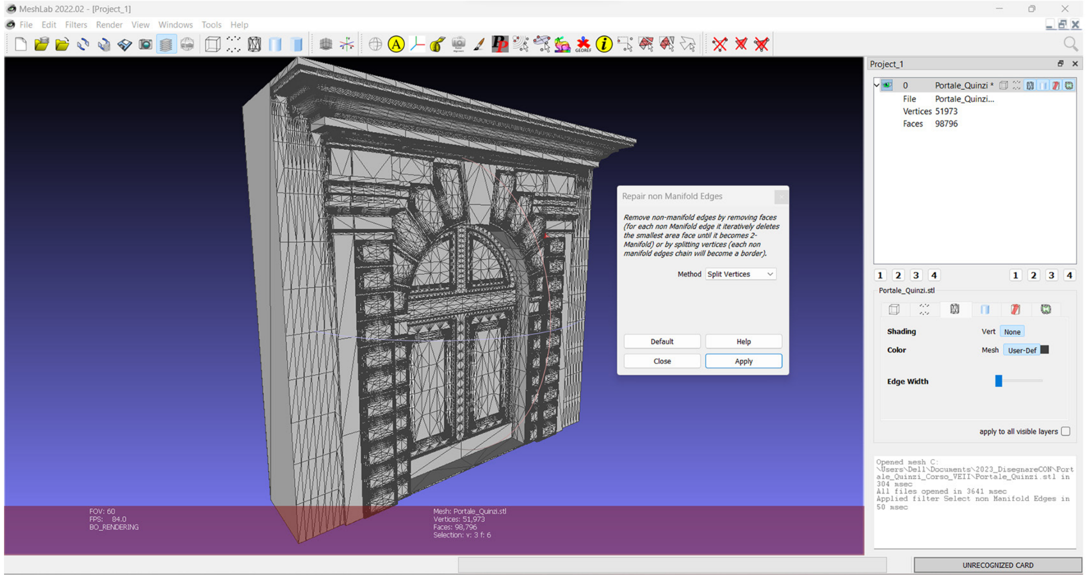
To create the portal's NURBS model (Di Paola, 2007), slices of the point cloud derived from the photogrammetric survey were extracted using CloudCompare (CC), a 3D cloud and mesh management and processing software. The single cloud slices exported from CC were imported in .e57 format within the Rhinoceros software (Fig. 5). A critical analysis of the imported slices was carried out to generate the profiles of the generatrix curves of the NURBS surfaces (Fig. 5c).

The surfaces of the NURBS model were created from the defined curves using different methods, i.e. applying linear extrusion and the sweep on one rail. At the end of the modelling process, a portal replica characterised by 205 surfaces and 67 polysurfaces was obtained (Fig. 6). During the modelling phase, particular attention was paid to verifying the direction normals of the modelled surfaces and checks were carried out on the joining and combining of the different surfaces and polysurfaces to avoid problems, such as overlapping portions of surfaces, during the export of the model into the slicing software.

In the next phase, the NURBS model was exported to create its physical replica in .stl (Standard Triangulation Language To Layer) format, a standard managed by the different slicing software for 3D printing. During the transformation of the NURBS objects into polygonal meshes, the main parameters to obtain triangles with different dimensions that follow the model profile and correctly approximate the curved surfaces were defined.

The mesh model resulting from the transformation into the .stl format, characterised by 99K faces, was imported into the opensource software MeshLab to check and correct possible defects, such as the creation of non-manifold edges and vertices, related to the passage from the NURBS model to the mesh one (Fig.7). The analysis of the mesh model highlighted the presence of three vertices and six non-manifold faces that were repaired by dividing the mesh vertices through the 'Repair non-manifold Edges' function (Fig. 7).

Fig. 6 – NURBS model of the portal.



Repair non Manifold Edges

Remove non-manifold edges by removing faces (for each non Manifold edge it iteratively deletes the smallest area face until it becomes 2-Manifold) or by splitting vertices (each non manifold edges chain will become a border).

Method: Split Vertices

0 Portale_Quinzi *
File Portale_Quinzi...
Vertices 51973
Faces 98796

Portale_Quinzi.stl
Shading: Vert None
Color: Mesh User-Def
Edge Width
apply to all visible layers ☐

```
Opened mesh C:
\Users\Dell\Documents\2023_DisegnareCON\Port
ale_Quinzi_Corso_VEII\Portale_Quinzi.stl in
304 msec
All files opened in 3641 msec
Applied filter Select non Manifold Edges in
50 msec
```

FOV: 60
FPS: 84.0
BO_RENDERING

Mesh: Portale_Quinzi.stl
Vertices: 51,973
Faces: 98,796
Selection: v: 3 f: 6

Fig. 7 – Mesh model derived from NURBS imported into MeshLab: identification and repair of non-manifold edges.

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3D PRINTING

The mesh model obtained from the photogrammetric survey process and the one resulting from the NURBS modelling were imported into the Simplify 3D slicing software for realising the physical replica of the analysed portal and thus testing the proposed workflow.

Simplify3D permits defining the most suitable parameters for printing the prototype, such as the nozzle diameter, layer height, number of perimeters, infill percentage and material information (bed temperature, extrusion temperature, etc.).

A layer height of 0.08 mm was set for the prototypes, ensuring a high vertical resolution of each printed layer and high printing accuracy. The envelope thickness was set at 1.20 mm while the filling percentage, namely the inner density of the printed object, was set at 20% with a hexagonal shape (Fig. 8). A raft was added to the base to improve adhesion to the printing plate and help with warping of the printed parts by setting the following parameters: (i) Raft Top Layers: 2; (ii) Raft Base Layers: 2; (iii) Raft Offset from Part: 5 mm; (iv) Separation Distance: 0.14 mm.

Finally, to prevent the creation of supports for overhangs, the photogrammetric mesh model, which has protruding elements at the base and the top, was placed horizontally on the 3D printer's printing plate (Fig. 9a). On the other hand, the model derived from the NURBS modelling was placed vertically by rotating it 180° so that the single protruding surface of the model, the upper portal frame, was in contact with the printing plate (Fig. 9b).

Finally, the different printing temperatures were specified. The extruder temperature was set to 250°, which is suitable for the ABS filament fusion and extrusion, guaranteeing an adequate adhesion

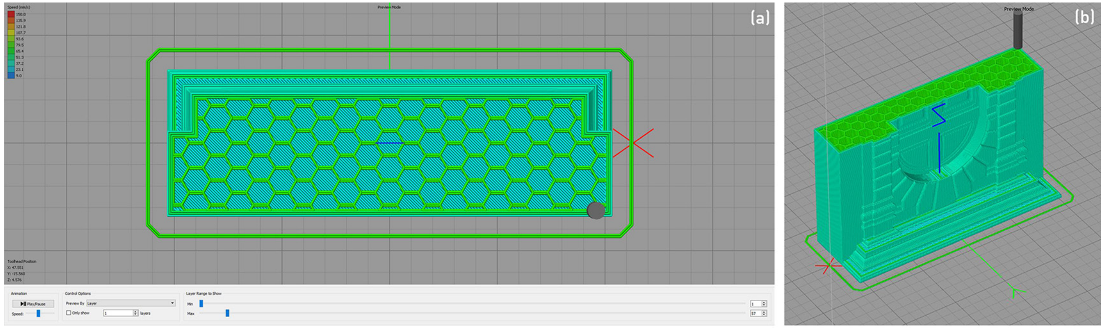

Fig. 8 – Features of the physical model to be printed: inner filling and layer thickness: (a) top view in the slicing software; (b) 3D view in the slicing software.

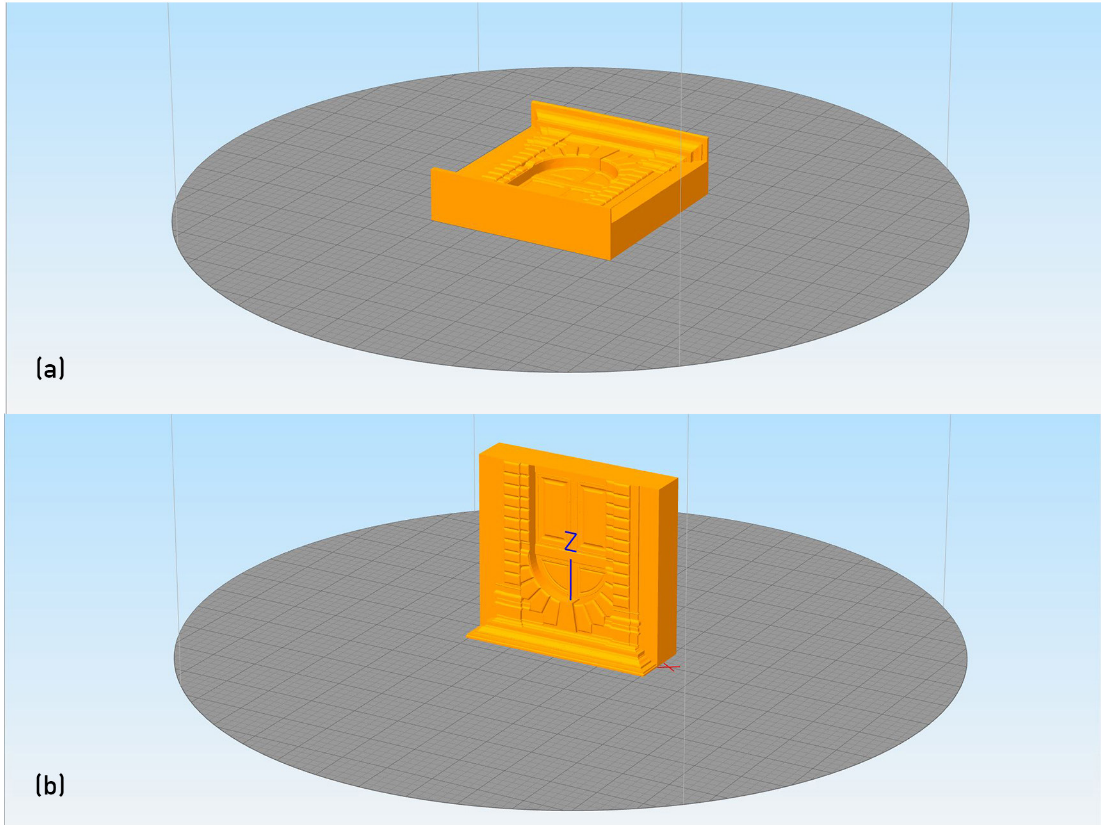

Fig. 9 – Simplify3D software view: (a)Photogrammetric model oriented horizontally to the printing plate; (b) NURBS model oriented vertically to the printing plate.

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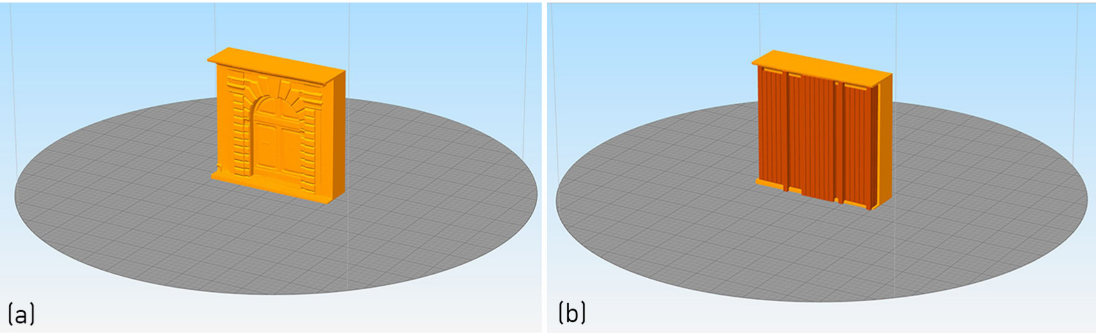

Fig. 10 – Photogrammetric model oriented vertically in the slicing software: (a) without supports; (b) with vertical supports.

Table 1 - Overview of 3D printing time, material consumed and prototype weight.

	Build time	Filament length [mm]	Plastic weight [g]
Prototype from photogrammetric model			
Scale 1:100 (vertical with support)	4h 12’	8257	24.8
Scale 1:100 (horizontal)	2h 09’	5652	17.0
Scale 1:50 (vertical with support)	24h 39’	46840	140.8
Scale 1:50 (horizontal)	10h 52’	29738	89.4
Prototype from NURBS model			
Scale 1:100	2h 24’	5586	16.8
Scale 1:50	11h 44’	30654	92.2

of the different layers and a constant print quality throughout the process. The bed temperature, on the other hand, was set at 95°.

In the last phase, the G-code was exported from the slicing software for making the different prototypes of the model. These physical replicas were made with the WASP 4070 ZX printer, which uses FFF (Fused Filament Fabrication) technology, an additive manufacturing technique thanks to which a solid object can be created by overlapping a fused filament. As mentioned above, the white ABS (1.75 mm diameter) was used during printing, while an extruder with a 0.4 mm nozzle was fitted to the printer. During the printing process, an adhesion problem of the prototype to the printing plate was detected. Therefore, the bed temperature was changed manually and increased to 100° to guarantee proper material adhesion to the printing plate.

During the print of the horizontally positioned photogrammetric model, the top surface of the print showed bumps and holes, a problem generally caused by an insufficient thickness or improper cooling of the top layer. Since the NURBS model was printed in a vertical position and having observed that printing the model in a horizontal orientation generates a greater number of imperfections due to drops and filaments generally caused by the extruder’s displacement (Inzerillo, & Di Paola, 2017; Marra, Vespasiano & Brusaporci, 2023), the photogrammetric model prints were made by placing the base parallel to the printing plate (model vertically placed) and generating vertical supports for the overhanging parts (Fig. 10).

At the end of the 3D printing process, four prototypes in two different scales, 1:100 and 1:50, were obtained from the photogrammetric mesh model (Fig. 11a) and the NURBS model (Fig. 11b). Table 1 summarises the time and results of the printing process.

RESULTS AND FINAL REMARKS

Digital surveying and 3D printing have brought enormous benefits to the analysis, documentation, and communication of cultural heritage. The combination of these techniques provides, in

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fact, a valuable support to the preservation and enhancement of cultural heritage as they offer the possibility of reproducing digital models and physical prototypes particularly detailed of peculiar and complex elements of the architectural heritage. Moreover, digital and physical models can encourage new forms of study and analysis of cultural heritage and encourage not only the dissemination of information arising from knowledge processes but also the accessibility of heritage to a much wider audience.

The research presented, aimed at defining an optimal workflow for the creation of physical models at different scales, has shown not only the effectiveness of digital tools in the acquisition of geometric information, but also the efforts necessary to obtain, through 3D printing, physical prototypes of peculiar elements of the historical heritage deriving from different modelling processes. These prototypes can support the processes of preservation and enhancement of architectural heritage on several levels, but the procedure tested in this research has highlighted some differences that, although minimal, must be considered according to the purpose for which the physical model is created (Fig. 12).

In particular, the first observation regarding printed models is related to the printing scale. Both models in scale 1:50 are more clear, legible, and effective than models in scale 1:100, also because of the lower impact of small imperfections related to the printing process. A minimum scale of 1:50 is recommended for architectural elements of this size. Comparing then the prototypes in scale 1:50 obtained from the model NURBS and that obtained from photogrammetry, it can be considered that both prove effective for analysis and documentation purposes, as well as for dissemination or enhancement. However, the prototype obtained from the NURBS model is clearer and more effective in

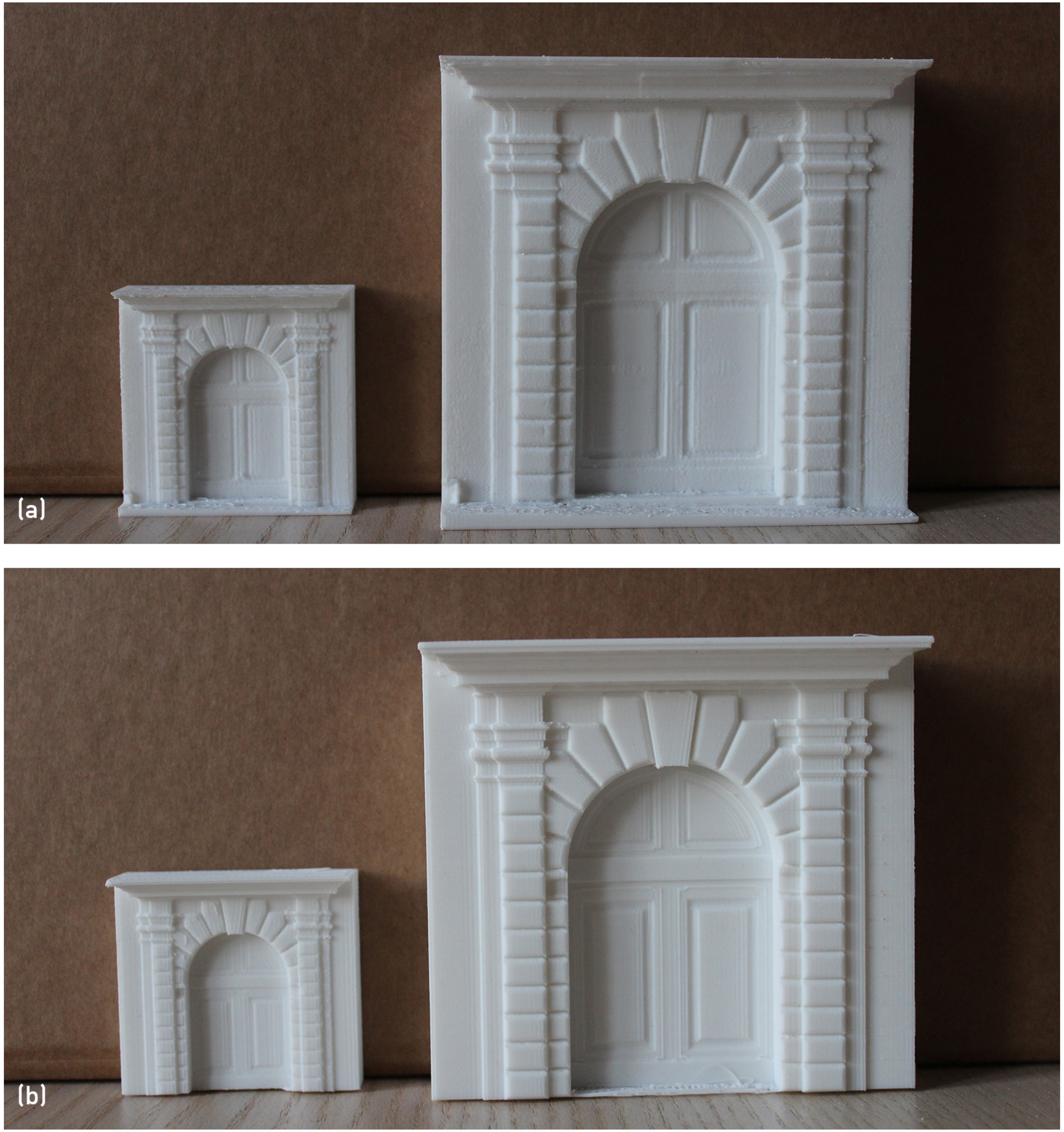

Fig. 11 – (a) Physical prototype derived from the photogrammetric model: on the right scale 1:50 and on the left scale 1:100; (b) Physical prototype derived from the NURBS model: on the right scale 1:50 and on the left scale 1:100.

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comparison by sight, difficult to document even through photography. Indeed, the sharpness and definition of the plastic surfaces and joints return with greater precision the characteristics of the original artefact. Therefore, it can be concluded that the further passage of critical interpretation and the increased effort in terms of work is justified by an improved final result.

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CREDITS

Although the paper was conceived as unit, Adriana Marra is the author of the sections Introduction, State of the art, The NURBS model: from survey to critical restitution, 3D printing; Luca Vespasiano is the author of the sections The case study: the portal of the Palazzo Quinzi, Photogrammetric survey and mesh model. Both authors wrote the paragraph Results and final remarks.

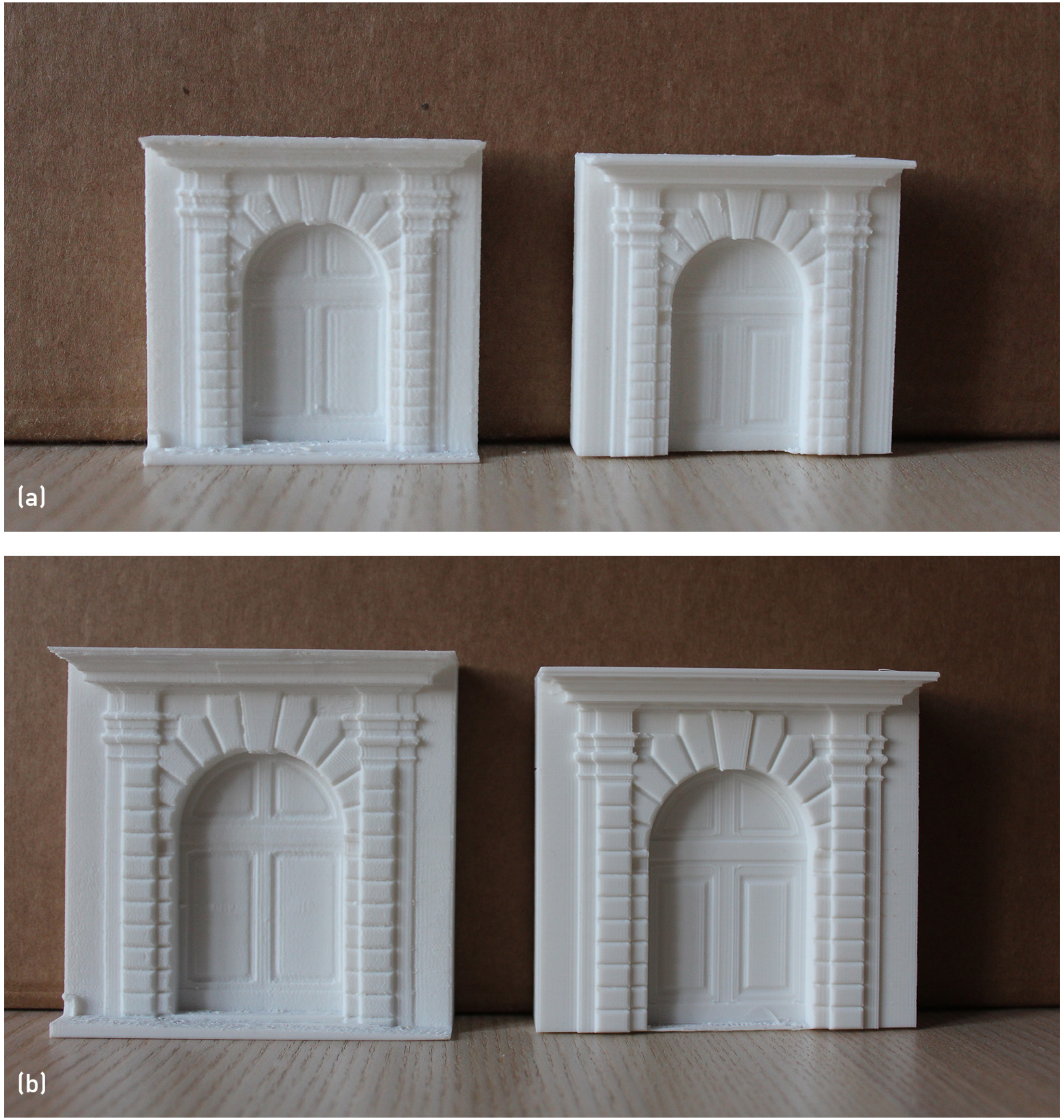

Fig. 12 – Comparison between the prototype obtained from the photogrammetric model, on the left, and the one obtained from the NURBS model, on the right: (a) scale 1:100; (b) scale 1:50.

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