Virtual Archaeology Review, **16**(33): NNs-NNe, 2025
https://doi.org/10.4995/var.2024.22610

Received: October 13, 2024
Accepted: January 12, 2025

DIGITAL RECONSTRUCTION OF BARROS LIMA'S DESIGN FOR SÃO TORCATO SANCTUARY, 1825

RECONSTRUCCIÓN DIGITAL DEL PROYECTO DE BARROS LIMA DESTINADO AL SANTUARIO DE SÃO TORCATO, 1825

Pedro de Azambuja Varela*, João Luís Marques, Afonso de Matos Silva

Universidade do Porto, Faculdade de Arquitectura, Via Panorâmica s/n, 4150-564 Porto. pvarela@arq.up.pt; jlmarques@arq.up.pt; up201808063@up.pt;

Highlights:

- The digital reconstruction of São Torcato Sanctuary successfully revived the unfinished architectural vision using advanced techniques like photogrammetry and parametric modelling, despite limited source material.
- The project introduced a layered approach to 3D modelling, with Levels of Development (LOD) guiding the process from the basic structures to decorative elements, ensuring a balance between historical accuracy and interpretative speculation.
- A seven-level uncertainty scale was employed to visually represent the confidence in different model sections, helping bridge gaps in missing data while maintaining transparency about the reconstruction's speculative aspects.

Abstract:

This study reconstructs the unfinished architectural project of the São Torcato Sanctuary, designed by Luís Inácio Barros Lima in 1825, using modern digital visualisation techniques. The objective is to create a three-dimensional (3D) model that accurately represents the sanctuary's interiors, facilitating broader public engagement with this historical structure. Employing a systematic methodology, we analysed historical documentation and employed photogrammetry and parametric modelling through Rhinoceros (Rhino) software to reconstruct key architectural elements. We established a metric identification system based on regional measurement units, enabling a cohesive modelling process despite challenges posed by distorted and incomplete source material. The modelling process was organised into Levels of Development (LOD), allowing for a hierarchical approach from basic geometries to intricate features. We utilised Grasshopper for the efficient generation of various openings and detailed cornices, while photogrammetry facilitated the accurate modelling of existing capitals and the baldachin. A critical component of this reconstruction involved quantifying uncertainty within the model, utilising a false colour scheme to represent varying levels of confidence in the accuracy of different elements based on source availability. The average uncertainty score of the model was determined to be 40%, highlighting the speculative nature of some components due to incomplete documentation. This digital reconstruction contributes significantly to the architectural narrative of the São Torcato Sanctuary and serves as a resource for future research and public education. Despite inherent uncertainties, the model provides valuable insights into an architectural vision that remains unrealised, underscoring the importance of digital methods in the preservation and interpretation of architectural heritage.

Keywords: digital reconstruction; architectural heritage; photogrammetry; parametric modelling; uncertainty quantification

Resumen:

Este estudio reconstruye el proyecto arquitectónico inacabado del Santuario de São Torcato, diseñado por Luís Inácio Barros Lima en 1825, utilizando técnicas de visualización digital modernas. El objetivo es crear un modelo tridimensional (3D) que represente con precisión los interiores del santuario, facilitando un mayor compromiso del público con esta estructura histórica. Empleando una metodología sistemática, analizamos la documentación histórica y utilizamos fotogrametría y modelado paramétrico a través del software Rhinoceros (Rhino) para reconstruir elementos arquitectónicos clave. Establecimos un sistema de identificación métrica basado en unidades de medida regionales, lo que permitió un proceso de modelado cohesivo, a pesar de los desafíos presentados por el material fuente distorsionado e incompleto. El proceso de modelado se organizó en Niveles de Desarrollo (LOD), lo que permitió un enfoque jerárquico, desde geometrías básicas hasta características intrincadas. Utilizamos Grasshopper para la generación eficiente de diversas aberturas y cornisas detalladas, mientras que la fotogrametría facilitó el modelado preciso de capiteles existentes y del baldaquino. Un componente crítico de esta reconstrucción consistió en cuantificar la incertidumbre dentro del modelo, utilizando una paleta en falso color para representar los distintos niveles de confianza en la precisión de los diferentes elementos según la disponibilidad de las fuentes. Se determinó que el índice promedio de incertidumbre del modelo era

*Corresponding author: Pedro de Azambuja Varela, pvarela@arq.up.pt

del 40%, lo que destaca el carácter especulativo de algunos componentes debido a la documentación incompleta. Esta reconstrucción digital contribuye significativamente a la narrativa arquitectónica del Santuario de São Torcato y sirve como un recurso en futuras investigaciones y educación pública. A pesar de las incertidumbres inherentes, el modelo ofrece valiosas perspectivas sobre una visión arquitectónica que permanece sin realizar, subrayando la importancia de los métodos digitales en la preservación e interpretación del patrimonio arquitectónico.

Palabras clave: reconstrucción digital; patrimonio arquitectónico; fotogrametría; modelado paramétrico; cuantificación de la incertidumbre

1. Introduction

The chosen case study is the unfinished architectural project for São Torcato Sanctuary designed by Luís Inácio Barros Lima (LBL), in a small town, São Torcato, near Guimarães. A three-dimensional (3D) model of the 19th century project is proposed, using modern digital visualisation techniques to recreate the interior space, which was never completed and has since disappeared.

The aim is to create a model closely resembling what could have been built, focusing on the interiors. The model must be accurate according to the existing drawings, so communication objects can be created, thus reaching a wider audience. To achieve these objectives, the methodology adopted involves the collection and analysis of historical documentation, photogrammetry techniques, and parametric modelling.

While the models presented in this study aim to closely represent the original design of São Torcato Sanctuary, they are still a work in progress. Ongoing refinements are to be expected as new data or design decisions emerge, ensuring the model continues to balance historical accuracy with interpretative reconstruction.

2. Historical background

São Torcato, who is believed to have been martyrised on February 26, 719, led a group of armed men in battle against the Moors and perished at the hands of Musa, an Arab leader. The unburied body of this saint is attributed to Torcato Félix, Archbishop of Braga, who also served as Archpriest of Toledo and Bishop of Iria and Porto.

According to local legends, to prove the sanctity of São Torcato, a spring of "healing water" erupted from the place where the incorrupt body of the saint was discovered. In that same place, the local population built a small chapel called São Torcato-o-Velho, where the saint's body remained until the construction of the monastery in the village of São Torcato in the 10th century, where the body was buried in a dedicated chapel (Brito & Faria, 2023; Magalhães, 2021).

The veneration of São Torcato led, in the first quarter of the 17th century, to the creation of a brotherhood that promoted and spread the medieval saint's cult. By the end of the 18th century, they found themselves compelled to attempt to renovate the old Romanesque monastery due to the growing number of pilgrims who annually venerated the saint. However, the project was abandoned because of its difficult access, and a new location was chosen for the construction of a larger and more ambitious sanctuary.

2.1. Barros Lima's design for a new sanctuary

At the beginning of the 19th century, King D. João VI granted the land for the new temple and authorised the subsequent transfer of the saint to the new church. With this authorisation, construction began in 1825, following the design of Luís Inácio de Barros Lima (Guimarães, 1764–1844), an architect from the Porto Board of Public Works. The design was in the late Baroque style, spacious, but very modest both in terms of volume and decoration. Barros Lima's drawings are still partially archived at the headquarters of the Brotherhood. Only the longitudinal section and transversal section drawings remain (Anacleto, 1997).

2.2. Construction and abandonment of the original design

The construction of the LBL's main chapel was completed in 1846, and the saint's body was translated to that new location in 1852. Later, in 1854, the grand wooden baldachin made by the master José Vieira –with reference to the baldachin of the *Santuário do Bom Jesus do Monte*– was added. LBL's drawings do not make any reference to the interior furniture or altars, although there is space for them to exist. The rest of the sanctuary was never completed, with only the foundations laid.

This project was however challenged by Cesário Augusto Pinto (Lisbon, 1825–Guimarães 1896), who, in 1866, approached the Brotherhood's board, dissatisfied with the characteristics of Barros Lima's design, as he believed it did not do justice to the name of São Torcato. He then suggested that a competition be held that same year. Thanks to the intervention of the *Associação de Arquitectos Civis e Arqueólogos Portugueses*, the suggestion was made to expand this competition to an international scale. As far as it is known, this was the first public international architectural competition in Portugal (Marques, 2023b).

The state of the construction led the commission to constrain the programme, forcing the exclusion of Greek and Roman styles while requiring the use of the existing structures, although allowing for some modifications. Each project was to include a floor plan, three elevations (front, side, and rear), three sections (longitudinal, nave, and transept), six sheets of details, a descriptive report, and a budget. A survey of the existing main chapel and foundations was made and sent to the participants. This survey has unfortunately been lost, but we know it existed as it is referenced in many letters written by Cesário Pinto. At the deadline, only three submissions were received, with the French architect T. I. Groux's proposal even arriving late, after the prises had been awarded. Thus, the Portuguese architect Luís Caetano Pedro d'Ávila took second place, and the Prussian architect Ludwig Bohnstedt won first place.

Ludwig Franz Karl Bohnstedt (LB), until then unknown in Portugal, presented an eclectic-style. He would go on to build significant works across Europe, such as the headquarters of the Bank of Finland in Helsinki and the Riga Theatre (Current National Opera).

Due to the requirement to use the pre-existing foundations and structures, the architect was forced to devise ingenious solutions to adapt the deficiencies of the previous design to his own. He achieved this by doubling the triumphal arches preceding the transept, addressing the width discrepancy between the main chapel and the nave. The interior of the church, following local tradition, was designed with exposed granite surfaces and plastered vaults. However, the architect's vision differed from what was expected, as the plastered surfaces of the vaults were intended to be painted with biblical scenes.

From the beginning of the sanctuary's construction, various difficulties were apparent, and it was foreseen that it would not be completed within the 19th century, due not only to the natural delay caused by the extensive granite masonry work –given the stone's extreme hardness– but also due to a shortage of financial resources (Cardoso, 1997).

2.3. Stage of completion

Cesário Pinto oversaw the project and directed the construction of the Sanctuary without charge until his death in 1896. In 1898, the Brotherhood of São Torcato appointed the architect José Marques da Silva to take over Pinto's role. By the time Marques da Silva took over, the façade had already been built up to the arcade level. He completed the remaining construction that can be seen today, making changes to the towers and the dome, which he did not live to see completed. The left tower had suffered significant cracks after being struck by lightning in 1912 and was partially rebuilt, with slight modifications to the original design.

Figure 1: Longitudinal Section by Luís Inácio Barros Lima. Arquivo da Irmandade de São Torcato.

Figure 2: Transversal Section through the nave and transept by Luís Inácio Barros Lima. Arquivo da Irmandade de São Torcato.

Later, in 1946, the relics of the saint were translated from LBL's main chapel into the LB's provisionally closed off nave. In 1947, his daughter Maria José Marques da Silva and her husband David Moreira da Silva succeeded him, contributing to the design of the stained-glass windows, metalwork, and flooring. To construct the new main chapel, the earlier one had to be demolished in 1973. The concrete dome that stands to this day was completed in 2006 (Marques, 2021). Due to this mix of older and newer construction methods, some studies were made to monitor the building's stability (Ramos, Aguilar, Lourenço, & Moreira, 2012).

3. Methodology

One of the first steps to start Luís Inácio de Barros Lima's model was to gather, process and analyse all the sources, either drawn, period photographs or photogrammetry of existing pieces. The analysis of the existing drawings allowed us to identify and understand the metric system of palms and poles used by the architect and how to employ it (Cunha, 2003).

The drawn sources were then scaled and correctly oriented in Rhino (v. 8) to better reference and visualise them. In the same software, 2D drawings were drafted over the references in order to enable the modelling process. (Centofanti, Brusaporci, & Lucchese, 2014; Delooze & Wood, 1991)

To model the sanctuary, a LOD approach was taken to better visualise the different stages of the design, and to be able to create the different parts of the model in a more orderly fashion (Graham, Chow, & Fai, 2018). Also, to create some of the more intricate parts of the model, we used parametric modelling (Burry, 1996; Burry & Kolarevic, 2003). For the creation of the complex geometries needed for the cornices and lower trims, the best way to have a greater level of control over this process was to use Grasshopper. (Bianconi, Filippucci, & Magi Meconi, 2019)

Finally, an uncertainty analysis was done by assigning a number to each part of the model using a seven-level scale and then calculating its average uncertainty (Apollonio, Fallavollita, & Foschi, 2022).

3.1. Primary and secondary sources

As primary sources, the present study considers the longitudinal section (Fig. 1), the transversal section through the nave and transept (Fig. 2), and two black and white photographs: one of the original floor plan drawing (Fig. 3), and an older one, from the main chapel interior with the baldachin (Fig. 4).

Both drawings were made and signed by Luís Inácio Barros Lima in 1824 (according to the study made by Regina Anacleto (Anacleto, 1997), using an ink and watercolour technique, and have a dimension of, respectively, 84 cm by 56 cm and 42 cm by 54 cm, both scanned with a resolution of 400 dpi. The photograph of the missing floor plan was taken during the 90s in the context of the investigation work done by Regina Anacleto, in black and white film with a dimension of 7 cm by 10 cm and scanned with a resolution of 600 dpi. The image of the main chapel's interior is an A4 print of the

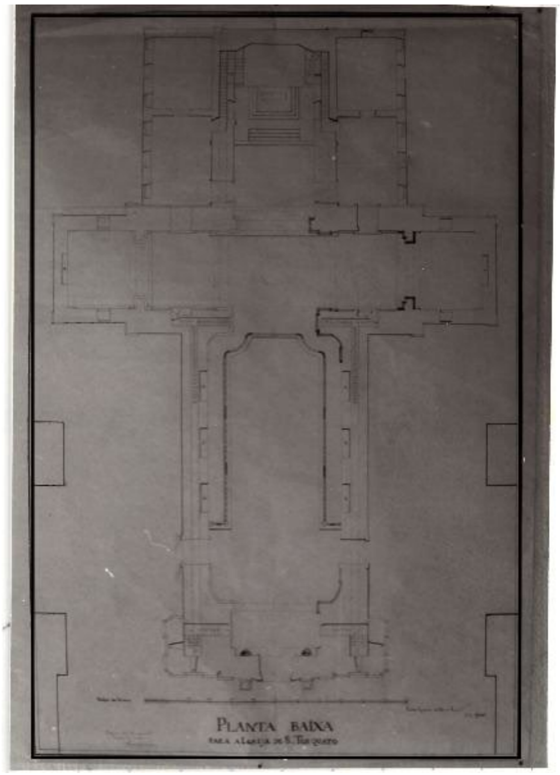

Figure 3: Photograph of the floor plan by Luís Inácio Barros Lima. Biblioteca Municipal de Arganil.

Figure 4: Poster with photograph of the main chapel with the baldachin. Arquivo da Irmandade de São Torcato.

original cliché photograph taken for the brotherhood for its dissemination in posters and postcards in the early 1900s.

Additionally, as secondary sources, there are two photographs where parts of the main chapel are shown: one is a 7 cm by 10 cm black and white film image where we can see the outside of the main chapel (Fig. 5). The second one is a much smaller, also black and white, image that shows the edification of the transept from Bohnstedt's project where we can briefly see the existing capitals and part of the cornice of the main chapel (Fig. 6). These were not considered as main sources due to their inadequate quality and to showing our subject as a secondary part.

Furthermore, two composite order capitals made of granite are found at the site (Figure 7a). These are, most likely, the ones seen in the small photograph mentioned before that were kept when the main chapel was dismantled and its stones sold. Unfortunately, we do not know where these stones could have been sold to, particularly the cornice and window frame masonries. In this way, the possibility of reaching an even greater rigor in the modeling of details is lost.

Alongside these, several pieces of the wooden baldachin are, to this day, kept in the brotherhood's museum (Fig. 7b). This baldachin suffered from a white termite attack circa 1940 that led to its dismantling and removal from the main chapel. In 1946 a new urn for the saint was designed in crystal and brass by Marques da Silva (Marques, 2023a).

3.2. Metric identification and legible geometry

Before starting the digital modelling process, a formal analysis of the existing drawings was necessary. CAD drawings were created to serve as references during the modelling phase in Rhino. During this process, we found

Figure 5: Outside view of the main chapel and transept. Colecção Fotográfica da Muralha - Repositório Casa da Memória.

Figure 6: Inside view of the transept. Arquivo da Irmandade de São Torcato.

(a) (b)

Figure 7: a) Granite capital stored inside the current church; b) Dismantled baldachin stored in the brotherhood's museum.

that the architect had used a system of measurement based on poles and palms, as was common at the time. To verify this, we delved lightly into this subject. According to Rui Maneira Cunha, and to the time and place of this project, the "Craveiro" System would be the correct one

Figure 8: Model section (crossing and main chapel) showing correspondence to the various Levels of Development used.

to employ, as seen in Table 1 (Cunha, 2003). A palm, traditionally defined as approximately 22 cm, became the base unit for scaling the entire structure. The pole, consisting of 5 palms, was measured at 1.1 m, forming the foundation for calculating the overall dimensions of the sanctuary. These conversions had to account for the slight regional variations in measurement standards

Table 1: Regional variation of the different units of measurement according to Rui Maneira Cunha.

Localidade	Vara	1/2 braça	Côvado	1/2 Vara	Pé = 1/2 Côvado	Palmo
Braga	1,10 (?)					
Guimarães				0,55		
Porto		0,92		0,55		
Telões						
Vila Real						
Lavandeira						
Ansiães						
Resende	1,09 (?)					
S. Martinho de Mouros	1,075		0,66			
Penedono					0,33	
Marialva						0,26 (?)
Castelo Rodrigo						
Pinhel			0,66			
Moreira de Rei			0,66			0,22 - 0,23
Algodres			0,66			
Sortelha			0,67			
Sabugal			0,663			
Monsanto			0,665			
Soure	1,05					
Montalvão						
Castelo de Vide						
Monforte		0,915		0,55		
Alandrial	1,10					
Redondo	1,10			0,56		
Monsaraz	1,083			0,55		
Moura	1,10		0,662			
Castro Marim			0,665			

(Table 1). Using the custom units function within Rhino allowed the use of the palm as the unit of measurement for the analysis and modelling processes.

Using this measurement system simplified the analysis process, as all dimensions fit neatly within a whole or half palm. According to the drawings the building would have had an approximate dimension of 41 by 59 poles (65 by 45 m) and a height of 19 poles (21 m). The modularity inherent in this system, with its reliance on repeated whole or half-palm units, created a rhythm and harmony in the design. Its simplicity facilitated communication between the architect and builders, ensuring that the construction process could proceed efficiently despite the complexities inherent in designing such a monumental structure.

Upon closer examination, it became clear that the black and white photograph of the existing floor plan could not also be used as a primary reference due to severe distortion and low resolution. As a result, we decided to redraw the floor plan, relying on the surviving sections and incorporating only minor details from other drawings. While this approach allowed us to create a more cohesive model, certain areas, particularly the transept, required adjustments since the sections alone did not provide sufficient information. These modifications were made to ensure that the final design stayed true to the overall architectural vision.

3.3. Levels of Development (LODs)

LODs are a critical component when creating digital models. These define several degrees of complexity and stages of development of a project. Originating from BIM practices, LOD frameworks help structure the progression from abstract geometries to fully detailed models.

To optimise the modelling process, a hierarchical approach was adopted, moving from broad forms to finer details, using a scale referenced in the BIMForum "Level of Development Specification" (Graham et al., 2018). Starting with LOD 200, where we can see the building in its purest form, the general shape was modelled by extruding the walls from the plan and closing the vaults and cupola. On the LOD 225 level, we start deepening the model's detail by subtracting spaces for windows, doors using and side altars Boolean subtraction operations in Rhino.

The LOD 250 now brings a closeness to the real building by adding detailed elements such as pilasters. The LOD 275, by incorporating cornices and lower trims aids the model to reach a closer sense of realism. Finally, LOD 300, with the addition of the existing capitals and baldachin that was not present in the original project's drawings, was built in the main chapel. This level shows us the closest form of what this sanctuary could have been. The baldachin was reconstructed using photogrammetry and adjusted via perspective matching to align with the photograph showing the same subject. At this level, window frames were also modelled by tracing them over the longitudinal section and using depth cues from photographs to estimate the appropriate profile extrusion. Figure 8 illustrates the progression from LOD 200 to LOD 300, highlighting the incremental addition of complexity in the model.

4. 3D modelling of LBL's design

To effectively manage the complexity of this 3D reconstruction, a sophisticated layer system was developed, utilising Rhino's layer states feature. This approach allowed for the organisation of various elements by groups based on LODs, facilitating both the visualisation and modelling processes. By assigning specific components of the building to different layers — such as walls, windows, cornices, and vaults— this system enabled easy toggling between parts of the model. This modular approach provided the flexibility to isolate and focus on specific sections without overloading the working environment, minimising the risk of errors during the modelling process. A synthesis of the parts and

Table 2: Semantic segmentation of the model.

		Mass	Openings	Pilasters	Cornices and Trims	Capitals and Frames	Uncertainty
São Torcato		LOD 200	LOD 225	LOD 250	LOD 275	LOD 300	40,01%
01. Main Chapel	01.1. Walls						25,29%
	01.1.1. Openings						
	01.1.1.1. Frame						
	01.1.1.2. Positives						
	01.1.2. Pilasters						
	01.1.3. Cornice Sup						
	01.1.4. Trim Inf						
	01.2. Vault						
	01.2.1. Openings						
	01.2.2. Pilasters						
02. Transept	02.1. Walls						42,58%
	02.1.1. Openings						
	02.1.1.1. Frame						
	02.1.1.2. Positives						
	02.1.2. Pilasters						
	02.1.3. Cornice Sup						
	02.1.4. Trim Inf						
	02.2. Vault						
	02.2.1. Openings						
	02.2.2. Pilasters						
03. Crossing	03.1. Walls						48,05%
	03.1.2. Pilasters						
	03.1.2.1. Capital						
	03.1.3. Cornice Sup						
	03.1.4. Trim Inf						
	03.1.5. Pulpit						
	03.3. Cupola						
	03.3.1. Lantern						
	03.3.2.1. Openings						
	03.3.2. Positives						
04. Nave	04.1. Walls						39,67%
	04.1.1. Openings						
	04.1.1.1. Frame						
	04.1.1.2. Positives						
	04.1.2. Pilasters						
	04.1.2.1. Capital						
	04.1.3. Cornice Sup						
	04.1.4. Trim Inf						
	04.2. Vault						
	04.2.1. Openings						
	04.2.1.2. Positives						
	04.2.2. Pilasters						
05. Towers	05.1. Walls						50%
	05.1.1. Openings						
	05.1.1.1. Frame						
	05.1.1.2. Positives						
	05.1.2. Pilasters						
	05.1.3. Cornice Sup						
	05.1.4. Trim Inf						
	05.2. Vault						
	05.2.1. Pilasters						
06. Floor							33,50%

LODs employed, which led to the generation of layers, can be analysed in Table 2 (De Luca, 2013).

This modelling process was inherently iterative, characterised by ongoing feedback and revisions. Each stage required careful evaluation against the existing sources, historical references, and comparative analysis with similar architectural examples. This iterative approach ensured that each adjustment brought the model closer to an accurate representation of the original sanctuary while maintaining fidelity to its intended design. As illustrated in Table 2, the layer organisation, although extensive, is structured in a way that allows the user to navigate the building's elements with efficiency. Each layer group is clearly labelled and colour-coded, enabling quick navigation through the building's elements and ensuring that any required modifications can be implemented with minimal disruption to the overall workflow. Each LOD had its own corresponding layers, from the base geometry of walls and volumes (LOD 200) to detailed architectural features like pilasters, cornices, and capitals (LOD 275 and beyond). Utilising Rhino's layer states feature proved to be a game-changer for managing the various components of the model. This feature allowed for the preservation of specific layer configurations, making it easy to switch between different states of the model as the design evolved.

The sanctuary's design is rooted in axial symmetry, a defining feature of Baroque architecture. This symmetry was integral to the 3D modelling process, providing a logical framework for reconstructing missing elements. For example, the longitudinal symmetry of the nave and main chapel and the double symmetry of the transept ensured proportional alignment, simplifying the extrapolation of incomplete sections. Additionally, the semi-circular geometry of the vaults proved advantageous for modelling, as their consistent curvature could be accurately reproduced. This was all instrumental in resolving the gaps present in the historical documentation and maintaining alignment with LBL's design principles.

4.1. Openings

With 38 openings across ten different typologies. Grasshopper was the most efficient tool to generate most of the corresponding opening positives (Fig. 9). As seen in Table 3, using parametric models was efficient since an algorithm was used in the generation of all windows, creating the various window positives. As is evidenced in Table 3, these openings have a broad range of purposes

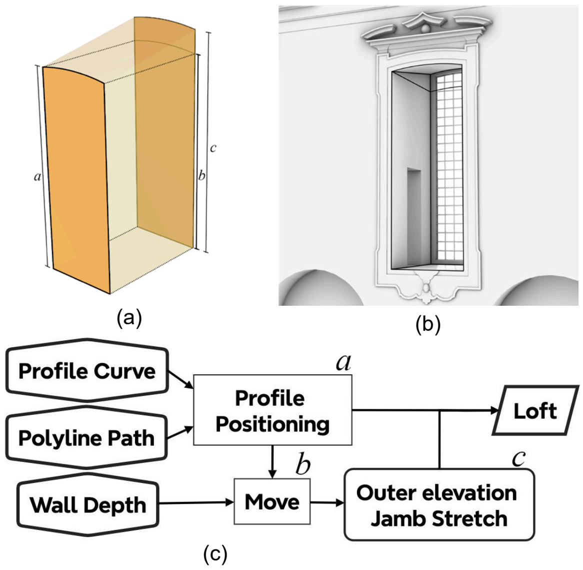

Figure 9: a) Geometric generation of subtractor; b) Subtractor within finalised architecture; c) Logical diagram of operation.

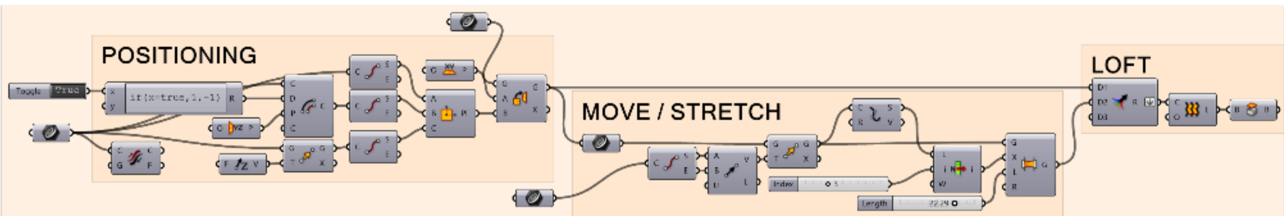

Figure 10: Grasshopper definition for window positive creation

Table 3: Table of openings.

Type										
Name	Window CM	Door CM	L Niche CM	Window NV	U R Window TR	L R Window TR	S Window TR	Door NV	U Niche CM	Niche TR
Ocurrences	6	4	2	6	2	2	4	2	2	8

and sizes, going from simple rectangular or circular windows to more complex niches in the walls as evidenced in the following four steps.

The first step, drawing and aligning the interior elevations of the window, focused on defining the exact geometry of the interior elevation of every window in such a way as to fit with the proportions from the historical drawings and then centring them on the centre xy plane.

The second step, localising the windows within the church, had the window profiles moved to their correct position on the church walls. Grasshopper was particularly helpful in this step because all the windows could be placed in rapid succession, allowing at the same time the ease of drawing on top of the sections.

The third step, related to parametrically modifying the elevation dimensions, due to the difference from inside face to outside face on window dimensions, used a parametric adjustment. This allowed for refinement in the size of each window by parametrically controlling the window jambs (Fig. 9).

The fourth step involved making the window volume positive: Since most windows taper outward vertically (as evidenced in the transversal section through the nave), the best course of action was to loft from the already placed elevation on the interior face of the wall to the exterior one, the latter being parametrically altered by stretching the jambs. Therefore, the interior and exterior faces were smoothly transitioned, and the resulting shape was capped for a closed polysurface to be produced.

In the last step, the obtained shapes were copied to their respective locations and the Boolean Difference operation was applied within Rhino by taking away the positive of the windows from the solid geometry of the wall. This creation process using Grasshopper allowed us to create all the different window positives using the same algorithm, thus streamlining the entire process.

4.2. Cornices and lower trims

For modelling the cornices and trims, the easiest way would have usually been to sweep the profile along a path. In this case, however, this was not enough because of the errors that appeared from the complexities of the polyline used as a path. These irregularities, such as self-intersecting shapes or the appearance of sections that extended beyond the polyline sections, were, of course, unwanted distortions in the final shape that required a subtler and more flexible solution. To fix this problem, the only other solutions would be to either manually position the profiles at each part of the polyline and extrude them or to solve the problem algorithmically in Grasshopper, creating a complex script that provided more control over the process and the possibility for cleaner geometry and better adaptability to surface complexities (Figs. 12 & 13). This method also helped to streamline the modelling process for all the different cornice and lower trim profiles.

Since there are varied construction methods optimised for distinct types of surface modelling, specific strategies were put into practice based on the geometry of each section. The process was divided into two parts: straight and curved sections.

Straight Sections: For the straight parts of the path, the use of a lofting technique proved to be most effective. This was done by placing the profile at each curve's midpoint and then projecting it onto planes created at the intersection points of the polyline segments. The resulting

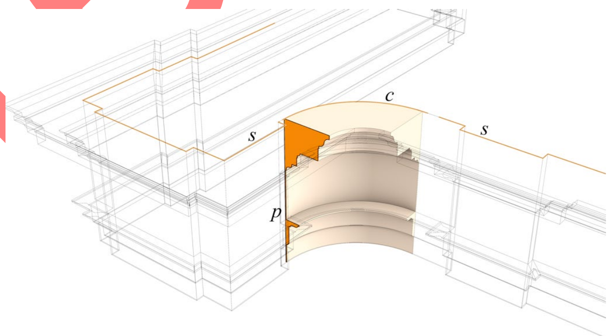

Figure 11: Profile in dark orange swept into the cornice in light orange (p, c, s corresponds to Fig. 12).

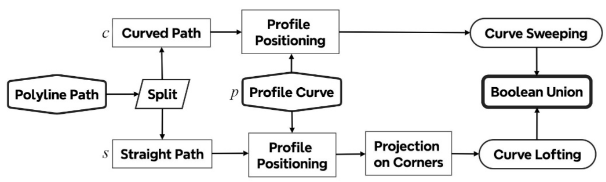

Figure 12: Diagram explanation of Fig. 11.

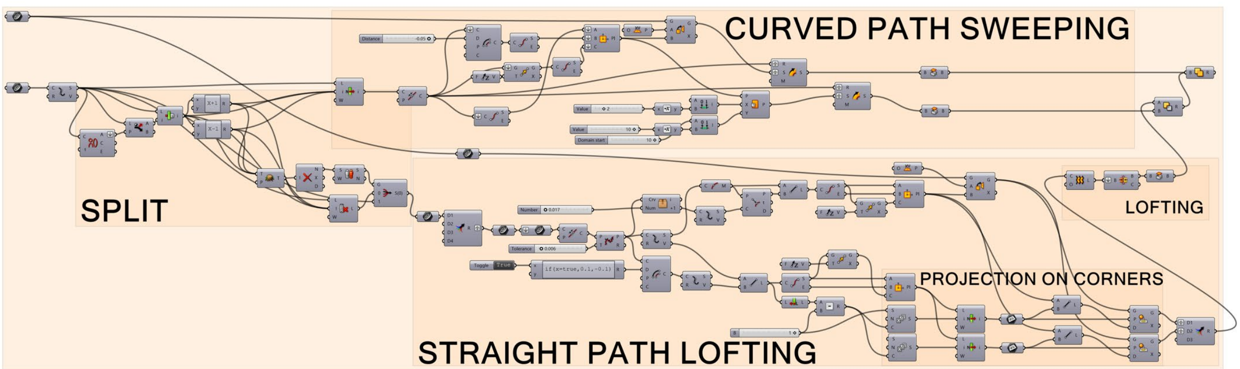

Figure 13: Grasshopper definition for cornice and trim creation.

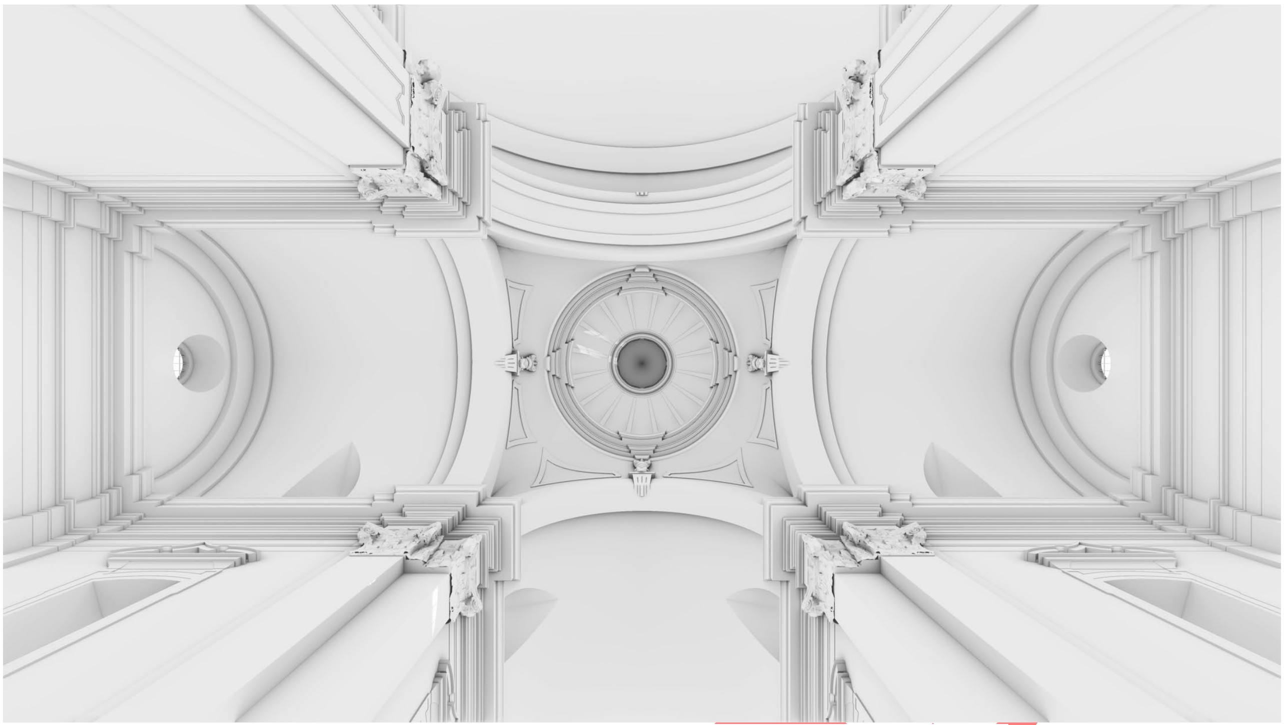

Figure 14: Perspective view of the reconstructed church towards the dome.

Figure 15: Reconstruction of the Baldachin: the area painted in orange refers to the photogrammetry mesh model, while the rest is explicitly modelled.

curves from these projections, when lofted, created the cornice with increased accuracy and much smoother transitions between segments.

Curved Sections: The curved sections presented a distinct set of challenges, requiring more sophisticated surface modelling. For these sections, a sweep operation was performed, but only after isolating the curved segments from the straight ones. Using a logic gate within Grasshopper, the path was analysed to detect the curved parts, which were then separated from the preceding and following straight lines. These parts group was joined with the straight segments found before and after. By isolating these curves, the sweep operation could be applied more effectively, preventing the distortions that might arise from an uneven transition between straight and curved paths (Fig. 12).

To create more accessible models, and ensure a better readability of the model files, the best course of action is to ensure that all shapes are closed solids, independently of the type of surface modelling applied. Thus, once the lofting and sweeping operations were completed, all resulting shapes were subjected to a Cap operation to form closed polys@urfaces. It is important to ensure that all resulting polysurfaces are closed, and further actions is needed if this is not the case. The final stage involved joining all these surfaces using a Boolean union process, ensuring that the cornices and trims formed continuous, uninterrupted elements, ensuring a better visualisation. This is related to the appearance of unwanted edges in computer-generated imagery, which are related to the elements' topology. Although we could relate this digital modelling topology to real-life construction elements defined limits, such as discrete unique stone dimensions, this type of information is not relevant to the scope of this work, more closely related to an idea of architecture design.

4.3. Capitals and baldachin

As identified above, two composite order capitals and various parts of the baldachin exist on site and were thus surveyed (Fig. 7b). For this task, we used photogrammetry via the Scaniverse v. 4.0.4 software, from where the resultant mesh was exported and introduced in Rhino for processing.

Once the raw mesh was imported into Rhino, the data required heavy processing to clean out noise arising from the scanning process. This entailed the use of commands like MeshReduce, to optimise the file for modelling purposes (geometrically accurate and of manageable size). After this processing, the capitals were placed in their appropriate locations according to the surviving drafted sections (Figs. 16 & 17).

The baldachin was only partially complete and proved more complex to complete its 3D model. Most of the pieces were found on-site, but some of the parts were missing and, therefore, needed analysis of the sources and digital modelling to fill in the gaps (Fig. 15). The making of the missing parts resorted to the analysis of similar baldachins, as is the case of the one present in the *Bom Jesus do Monte* Sanctuary in Braga, and careful study of the existing photographs to make an educated guess about the original design. Once all pieces were assembled digitally, the next task was to position the columns and the baldachin correctly within the church.

To understand the position of this element within the church's apse, a process of perspective matching was undertaken to achieve proper alignment of the elements with the historical photograph (Fig. 4). It involved overlapping the photograph and the digital model and manipulating its scale, rotation, and position to match the perspective represented in the image. That way, the final montage of the baldachin inside the main chapel was as precise as possible regarding the scale and spatial relations that were to be reflected in the original.

Figure 16: Photogrammetric model of one of the granite capitals.

5. Uncertainty scale

In the scope of digital reconstruction, the ability to quantify and easily identify the uncertainty of a model is crucial. For scientific purposes, it is important to know how accurate each model is and how were the available sources used. False colour models are an effective way to visualise this variations since just by looking at an image we can understand how accurate the model is.

Figure 17: a) Transversal section through the transept of the reconstructed church; b) Longitudinal section of the reconstructed church; c) Transversal section through the nave of the reconstructed church; d) Plan of the reconstructed church.

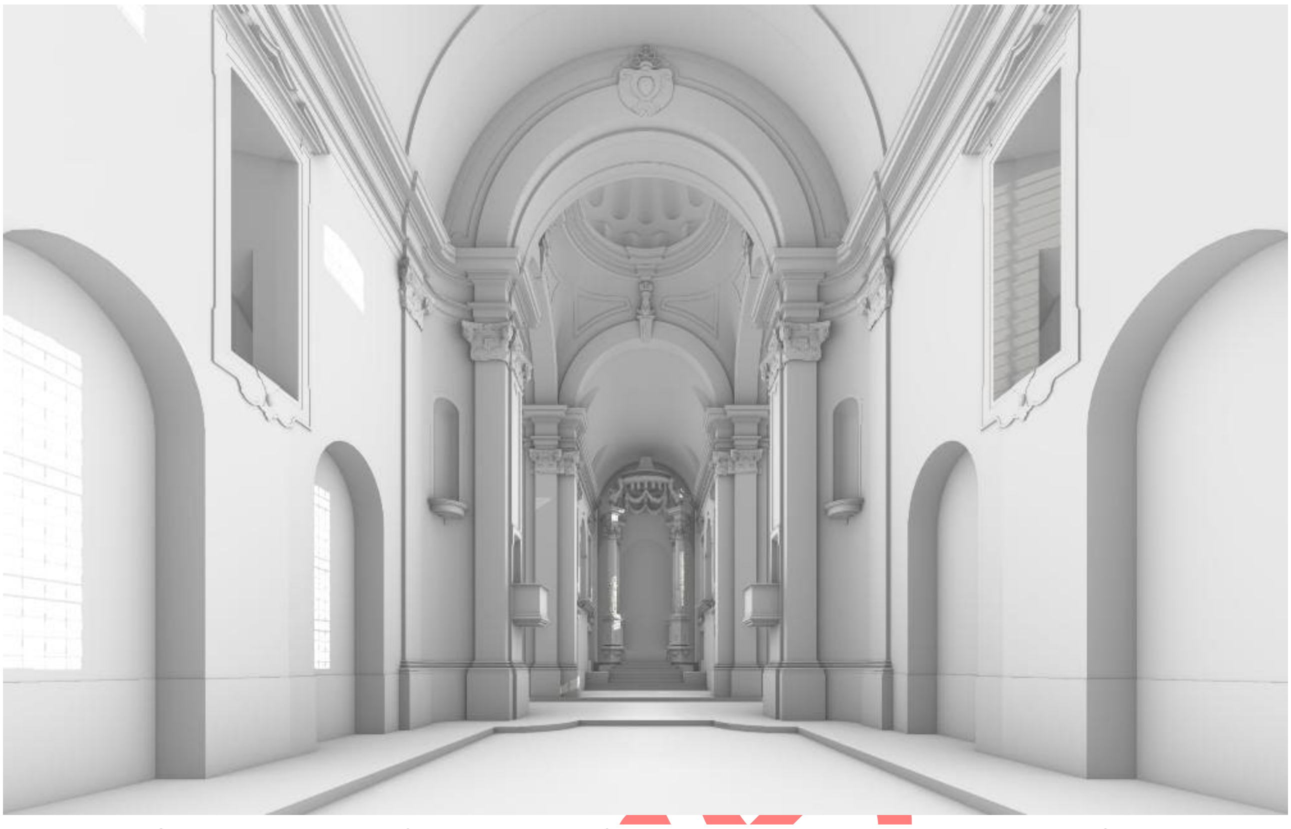

Figure 18: Central perspective view of the reconstruction of Luís Inácio Barros Lima's design with the addition of the baldachin.

Due to the lack of source availability, there are some well-understood limitations. This digital model of São Torcato Sanctuary carries an inherently higher uncertainty score. This score reflects the varying degrees of confidence we have in the accuracy of different elements of the reconstruction based on the quality and quantity of available information. This is influenced by incoherence between the heights in the various sections and the fact that the original plan is preserved only in the form of a poor-quality photograph. Several assumptions had to be made (Fig. 17), though many of these were confirmed by comparison with other similar buildings of the same period and style. These provided reference points that served to bridge some of the gaps left by the absence of direct sources.

One of the primary sources that helped confirm some of the details in the model is the interior photograph of the sanctuary, which confirmed the shape of the cornices and provided clues about the window frames. Nevertheless, most of the model remains speculative to one degree or another, since in many instances direct visual or written references are lacking.

A false colour model – Fig. 19 - was produced to display and explain the varying degrees of uncertainty within the model, visually transposing the varying levels of certainty that have been assigned to various parts of the reconstruction (Foschi, Fallavollita, & Apollonio, 2024). The seven-level scale for this model colours each segment, from Red (level 7), the most extreme level of uncertainty, representing something based only on personal knowledge due to missing or unreferenced sources. To White (level 1), the least uncertain, which is a part of the model derived mainly from good quality reality-based data. This progression is based on a gradient of colours that covers the visible spectrum, making it easy to see which parts of the model are more speculative and which are more reliable.

The subsequent colours are orange (level 6), which is defined by conjectures based on indirect or secondary sources of similar works by different authors; yellow (level 5), representing conjectures based on indirect or secondary sources by the same author; green (level 4), representing minimally unclear primary sources that do not reach the required corresponding LOD; light blue (level 3), representing mainly logical deduction; and dark blue (level 2), representing reliable conjecture based primarily on clear, accurate, direct sources that meet the target LOD.

There is also an additional eighth level for parts excluded from the model, but still relevant for defining the spatial relationships within the overall structure. These excluded parts do not contribute to the uncertainty score, but play a role in supporting the integrity and interpretation of the model.

By assigning a number to each part of the model, an average can be calculated based on the overall volume of the structure. To calculate this model's uncertainty, we used the AU_V formula (Foschi, Fallavollita, & Apollonio, 2024). This formula quantifies uncertainty in reconstructed models based on data quality and source completeness. The 40% uncertainty score was calculated by considering each segment's reliability on a scale from 1 to 7, with levels defined from direct, accurate sources to more speculative approximations. This model not only serves as a visual aid but also acts as a critical analytical tool. The chosen gradient from red to white not only visually conveys uncertainty levels but also allows for a quick assessment of which areas of the model demand further scrutiny or research. This method of uncertainty evaluation was chosen above others, due to its ease of

Figure 19: False colour model showing uncertainty levels.

comprehension and use. The various levels allow for someone not well versed in the topic to easily understand the amount of uncertainty presented, while the formula gives a more precise uncertainty quantification. (Kensek, Dodd, & Cipolla, 2004).

6. Discussion

This reconstruction applied a comprehensive methodology addressing the challenges of incomplete documentation by integrating archival research and comparative analysis to resolve gaps and uncertainties. Our aim was to be able to create a replicable approach to be used in other heritage sites lacking physical remains, serving as a model for integrating archival and digital tools. By using an approach based on a complex layer system and LOD organization, we were able to better segment the model and, thus, the work associated with it, as is seen in the proposal by De Luca (2013). Although the process was continuously evolving, introducing new subjects of work, the segmentation allowed for the seamless integration of additional layers within different layer groups, ensuring better organization of the overall data. Furthermore, the LOD organization associated with the layer states allowed going back and forth in the modelling process, thus helping the identification of errors and handling without the visual clutter of unneeded detailed parts.

The above strategy shows how the whole process was inherently iterative, as constant comparison with historical references was needed to refine specific parts of the model such as the reconstruction of the baldachin or the connection from the transept's crossing arches to the cupola. The use of parametric modelling also greatly helped in this iterative process, for example, in the creation of the window and door openings. By comparing methodologies with projects such as the Valencia Oil Market reconstruction (Llopis Verdú, Gutiérrez-Pérez, & Cabodevilla-Artieda, 2024), this study underscores the importance of interdisciplinary approaches in resolving dimensional ambiguities and fostering transparency in speculative models. While the Valencia Oil Market study focused heavily on resolving urban dimensional inconsistencies, our approach integrated parametric modelling to address complex elements like the dome transitions and cornices.

Geometric challenges arose, such as the appearance of unwanted modelling artefacts and self-intersecting solids in the process of the creation of cornices and lower trims. Thus, Grasshopper was key in allowing for greater control over how every segment was controlled, as parametric modelling was found to be the only efficient way to solve these issues.

While photogrammetry was essential for adding spatial coherence and detail to the baldachin and capitals, it also presented challenges, particularly with completing missing sections through speculative additions. On the other hand, the scanned capital did not correctly fit in every pilaster, needing transformation adjustments by either stretching or scaling. The final textured and abstract visualisation highlights the sanctuary's spatial essence while maintaining its interpretative openness, mirroring methods used in reconstructions like those of Bassoli, Fallavollita, & Fuchs (2022).

Due to the lack of information present in most of the sources, this model ca not obtain all the certainty it could have otherwise had. As such, some assumptions had to be made in the pursuit of completeness. Regardless of this, the uncertainty score of 40% is quite descriptive of the model accuracy, given that this result is obtained by measuring the volumes and their overall uncertainty. The false color model shows this quite well, as blues and greens are the most prevalent color, avoiding the uncertain yellows and reds by giving the color of each level to different parts of the model. This reconstruction demonstrates how digital tools can bridge gaps in historical knowledge, offering a model for interdisciplinary approaches that balance scientific rigour with interpretative creativity, fostering both academic research and public engagement.

7. Conclusions

This digital reconstruction project successfully recreated a detailed and plausible representation of the unfinished São Torcato Sanctuary, particularly its interior, through by harnessing a combination of historical documentation, photographs, objects and advanced modelling techniques. The process faced significant challenges, including missing floor plans and discrepancies in surviving drawings, which necessitated interpretation and adjustment. However, by using tools such as photogrammetry and parametric modelling, key architectural elements (such as the capitals and baldachin) were accurately reconstructed, offering valuable insight into the original design (Figs. 15 & 16).

This project highlights the crucial role that digital reconstruction plays in the preservation and interpretation of architectural heritage. By reconstructing the São Torcato Sanctuary, the project not only contributes to the architectural history of the region but also serves as a significant resource for future research, education, and public engagement.

While some uncertainties remain, especially in areas with limited source material, reliable references, such as the interior photograph, allowed for greater accuracy in the 3D reconstruction of features like window frames and cornice shapes. Despite the inherent limitations, the resulting model provides a thoughtful and well-founded approximation of the sanctuary's design, shedding light on an architectural vision that was never fully made.

Looking ahead, this project demonstrates how digital methods can expand our understanding of architectural heritage, potentially informing the reconstruction of similar sites. This digital model serves as a foundation for future work, whether through continued refinement, integration with interactive technologies, or as a reference for scholars and practitioners in heritage preservation.

Acknowledgements

We thank the *Irmandade de São Torcato* (São Torcato Brotherhood) for easing access to various spaces and consultation of archives and FAUP's DFL (Digital Fabrication Laboratory) for providing equipment and expertise for the development of this research.

References

Anacleto, M. R. D. B. T. (1997). *Arquitectura Neomedieval Portuguesa* (Vol. 1). Lisboa: Fundação Calouste Gulbenkian.

Apollonio, F. I., Fallavollita, F., & Foschi, R. 2021. The Critical Digital Model for the Study of Unbuilt Architecture. In F. Niebling, S. Münster, and H. Messemer (Eds.), *Research and Education in Urban History in the Age of Digital Libraries* (pp. 3–24). Cham: Springer International Publishing.

Bassoli, I., Fallavollita, F., & Fuchs, W. (2022). Hypothesis of reconstruction of the Roman theater of Urbs Salvia. *SCIRES-IT - SCIentific RESearch and Information Technology*, *12*(1), 151–164. https://doi.org/10.2423/i22394303v12n1p151

Bianconi, F., Filippucci, M., & Magi Meconi, F. (2019). Parametrical Vitruvius. Generative modeling of the architectural orders. *SCIRES-IT - SCIentific RESearch and Information Technology*, *8*(2). https://doi.org/10.2423/i22394303v8n2p29

Brito, F., & Faria, R. (2023). A história da vila e do culto a São Torcato. In *São Torcato: História, devoção e património*. Guimarães: Município de Guimarães.

Burry, M. (1996). Parametric design and the Sagrada Familia. *Arq: Architectural Research Quarterly*, *1*(4), 70–81. https://doi.org/10.1017/S1359135500003092

Burry, Mark, & Kolarevic, B. (2003). Between Intuition and Process: Parametric Design and Rapid Prototyping. In B. Kolarevic (Ed.), *Architecture in the Digital Age: Design and Manufacturing,* 1st Edition (pp. 148–162). London: Taylor & Francis. https://doi.org/10.4324/9780203634561

Cardoso, A. (1997). *O Arquitecto José Marques da Silva e a arquitectura no Norte do País na primeira metade do séc. XX* (2nd ed., Vol. 1). Porto: Faculdade de Arquitectura da Universidade do Porto. Biblioteca da Faculdade de Arquitectura da Universidade do Porto (M.P.73.1).

Centofanti, M., Brusaporci, S., & Lucchese, V. (2014). Architectural Heritage and 3D Models. In P. Di Giamberardino, D. Iacoviello, R. Natal Jorge, & J. M. R. S. Tavares (Eds.), *Computational Modeling of Objects Presented in Images* (pp. 31–49). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-04039-4_2

Cunha, R. M. M. (2003). *As medidas na arquitectura, séculos XIII - XVIII. O estudo de Monsaraz*. Casal de Cambra: Caleidoscópio.

De Luca, L. (2013). 3D Modelling and semantic enrichment in cultural heritage. *Photogrammetric Week'13*. Retrieved from https://hal.science/hal-02892090/

Delooze, K., & Wood, J. (1991). Furness Abbey survey project–The application of computer graphics and data visualisation to reconstruction modelling of an historic monument. In K. Lockyear & S. Rahtz (Eds.), *CAA90. Computer Applications and Quantitative Methods in Archaeology 1990* (BAR International Series 565, pp. 140–148). Oxford (United Kingdom): Tempus Reparatum.

Fallavollita, F., Foschi, R., Apollonio, F. I., & Cazzaro, I. (2024). Terminological Study for Scientific Hypothetical 3D Reconstruction. *Heritage*, *7*(9), 4755–4767. https://doi.org/10.3390/heritage7090225

Foschi, R., Fallavollita, F., & Apollonio, F. I. (2024). Quantifying Uncertainty in Hypothetical 3D Reconstruction—A User-Independent Methodology for the Calculation of Average Uncertainty. *Heritage*, *7*(8), 4440–4454. https://doi.org/10.3390/heritage7080209

Graham, K., Chow, L., & Fai, S. (2018). Level of detail, information and accuracy in building information modelling of existing and heritage buildings. *Journal of Cultural Heritage Management and Sustainable Development*, *8*(4), 495–507. https://doi.org/10.1108/JCHMSD-09-2018-0067

Kensek, K. M., Dodd, L. S., & Cipolla, N. (2004). Fantastic reconstructions or reconstructions of the fantastic? Tracking and presenting ambiguity, alternatives, and documentation in virtual worlds. *Automation in Construction*, *13*(2), 175–186. https://doi.org/10.1016/j.autcon.2003.09.010

Llopis Verdú, J., Gutiérrez-Pérez, N., & Cabodevilla-Artieda, I. (2024). Virtual reconstruction of the disappeared Valencia Oil Market (Spain). *Virtual Archaeology Review*, *15*(31), 86–103. https://doi.org/10.4995/var.2024.21148

Magalhães, J. L. D. T. (2021). *Entre o mito e a história. A construção da memória de São Torcato de Guimarães nos séculos XVI e XVII*. Porto: Faculdade de Letras da Universidade do Porto. Retrieved from https://hdl.handle.net/10216/139772

Marques, J. L. (2021). *São Torcato, a construção de um santuário: Leitura do projeto a partir do espólio de Marques da Silva*. Porto: Fundação Marques da Silva. Retrieved from https://issuu.com/fundacaomarquesdasilva/docs/s_torcato

Marques, J. L. (2023a). Arquitectura(s) para São Torcato: Barros Lima, Bohnstedt, Marques da Silva. In *São Torcato: Romaria a um vale infindável*. Guimarães: Município de Guimarães.

Marques, J. L. (2023b). SIT 1867, a arquitectura (des)conhecida de Ludwig Bohnstedt. In *São Torcato: História, devoção e património*. Guimarães: Município de Guimarães.

Ramos, L. F., Aguilar, R., Lourenço, P. B., & Moreira, S. (2012). Dynamic structural health monitoring of Saint Torcato church. *Mechanical Systems and Signal Processing*, *35*(1–2), 1–15. https://doi.org/10.1016/j.ymssp.2012.09.007