Learning from the 18th heritage through parametric modelling: case study of the National Palace of Mafra

Aprender com o património do século XVIII através da modelação paramétrica: estudo de caso do Palácio Nacional de Mafra

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Abstract

The 18th century in Portugal was a time of grandiose constructions, marked by the construction of the National Palace of Mafra (NPM), listed as a UNESCO World Heritage Site since 2019. Our understanding of this heritage is limited due to the minimal documentation that has survived to the present day. In this research, we address the lack of stereotomic studies, focusing on developing a methodology to document and model these constructive solutions. Our methodology includes the inventory of the stereotomic solutions, surveying with laser scanning and/or photogrammetry, understanding the generative geometric principles, and generating parametric models. Within the scope of this paper, we address one vault that, when represented as a parametric model, can be reused to fit other vaults of the NPM or of the same type in other buildings. These results represent an initial step toward developing a reusable library of stereotomic solutions for surveys and contemporary designs.

KEYWORDS
UNESCO World Heritage
National Palace of Mafra
Stereotomy
Point Cloud
3D parametric modelling
Digital heritage

Resumo

O século XVIII em Portugal foi um período de construções grandiosas, marcado pela edificação do Palácio Nacional de Mafra (NPM), classificado como Património Mundial da UNESCO desde 2019. A nossa compreensão deste património é limitada devido à escassa documentação que chegou até aos nossos dias. Nesta investigação, abordamos a falta de estudos estereotómicos, centrando-nos no desenvolvimento de uma metodologia para documentar e modelar estas soluções construtivas. A metodologia inclui o inventário das soluções estereotómicas, o levantamento através de varrimento laser e/ou fotogrametria, a compreensão dos princípios geométricos geradores e a geração de modelos paramétricos. No âmbito deste artigo, é analisada uma abóbada que, quando representada como modelo paramétrico, pode ser reutilizada para outras abóbadas do PNM ou de tipologia idêntica noutros edifícios. Estes resultados representam um passo inicial para o desenvolvimento de uma biblioteca reutilizável de soluções estereotómicas para levantamentos e projetos contemporâneos.

PALAVRAS-CHAVE
Património Mundial da UNESCO
Palácio Nacional de Mafra
Estereotomia
Nuvem de pontos
Modelação paramétrica 3D
Património digital

Introduction

The National Palace of Mafra (NPM), listed as a UNESCO World Heritage Site since 2019, is the main exemplar of a shift in architectural construction that took place in the eigtheenth century in Portugal [1-2]. As the main representative of stone stereotomic solutions of this period in Portugal, it was chosen as a case study. This paper focuses on developing a documentary methodology for stereotomic solutions through laser scanning and parametric modelling. To test the methodology, one specific vault was chosen at the ground level, beneath one of the bell towers.

We show the possibility of extending the application of parametric modelling methodologies to heritage contexts, where reverse engineering can provide a deeper understanding of the geometrical properties of existing structures [3-5]. Comprehending heritage remains challenging due to the scarcity of original project drawings and the limited surviving documentation. In the case of the NPM, only a few drawings of the building have survived [6], and no original documentation of the researched vault is known. In fact, we do not even know whether a stereotomic project was carried out in preparation for the stone cutting, or if this was prepared on site during construction. However, advancements in survey techniques offer promising avenues towards achieving a more thorough understanding of historical design methodologies [7-8]. The analysis of point cloud data led to a conceptual framework of the design of the vault. This was done through a parametric approach that, in turn, allowed us to consider the studied vault as an instance of a larger family of vaults, i.e. vaults that can be generated by changing the parameter values in the parametric model. In the specific case of the studied vault, the parameters were adjusted to make the parametric model fit the survey data. The recreated parametric model allows a deeper understanding of the structure's features, providing insights into the constructive process.

This study is a component of an ongoing PhD project focused on integrating stereotomic and geometric data sourced through the analysis of historical documents, photogrammetry, and laser scanning, to create parametric 3D models. The main objective of the first phase of the research was to streamline the process of generating parametric 3D models from survey data, creating an adjustable parametric object library of eighteenth-century Portuguese architecture based on the NPM. The database of characteristic building instances would enable the fast and effective creation and editing of 3D models of other buildings from the same period. This paper focuses on the geometric information and workflow of the geometric parametric 3D models.

Stereotomy

Stereotomy is the study of the material cut for construction with a structural purpose, mainly based on geometrical rules. It can be, for example, stone or wood, usually depending on locally available resources or the intended type of construction. The tradition of stone construction, at least in Western Europe, lasted until the end of the nineteenth century and was later superseded by concrete. Knowledge of classical stereotomy is visible in existing buildings and in architectural treatises such as those by Derand [9], Desargues [10], Frézier [11], de La Hire [12], or de Vandelvira [13], among others. The geometrical speculations presented in these written works include ways of constructing specific shapes such as arches, vaults, and domes, sometimes with references to existing constructions, including those located outside the author's country of origin. A direct connection to an example of Portuguese heritage exists in the treatise *La theorie et la pratique de la coupe des pierres et des bois pour la construction des voutes et autres parties des Bâtimens Civils & Militaires, ou Traité de Stereotomie a l'usage de l'Architecture* (vol 3), where the author points to the beauty and quality of execution of the sixteenth century vaults of the monastery of Belém's church [11].

Portuguese stereotomy is not widely studied, biggest focus of existing research being on the sixteenth century [3, 5, 14-15]. A brief introduction to stereotomy of this part of western Europe was also published in a study by Calvo-López [4], which points to already mentioned researchers that focus mostly on sixteenth century.

Despite the remarkable stone craftsmanship of eighteenth-century Portuguese architecture, it has been little studied from a geometrical perspective. This period introduced standardised architectural elements, repeated within buildings and shared by masons across sites, yet the geometric vocabulary of the time remains underexplored. Research in stereotomy has mainly addressed vault geometry, such as the nineteenth-century Arco da Rua Augusta in Lisbon [7]. Advanced survey techniques, including terrestrial laser scanning and photogrammetry, now allow a deeper understanding of historical design methods where original documentation is incomplete or unknown [8].

National Palace of Mafra and its relevance in the research

The National Palace of Mafra is a symbol of the Portuguese Golden Age and the backdrop for José Saramago's renowned novel [16]. Designated a UNESCO World Heritage Site in 2019, it has significant cultural and historical importance, supporting both preservation and scholarly research. Notable for its vast scale and symmetrical quadrangular layout, the palace serves religious, entertainment, educational, and residential functions [17]. The palace's remarkable architectural form owes its existence to the cultural and economic milieu of the Portuguese Empire during the reign of King João V, who enlisted international architects and artists to realise the NPM, drawing inspiration from the artistic aesthetics of Italian Baroque [18].

Located 30 km northwest of Lisbon, the palace-convent represents a paradigm shift in Portuguese construction. It was envisioned as a representation of the values and power of the Portuguese Empire, embodying Baroque artistic and architectural principles. The genesis of this palatial complex can be traced back to the establishment of the Convent of St. António in the village of Mafra, pursuant to the charter issued by Dom João V in 1711. Initially conceived as a modest convent in the typology of the Arrábidos Friars, the project expanded over time to accommodate a larger community of friars and a church [6]. The construction of the Basilica began on 17 November 1717, during the Johannine period, and continued until King João V's death in 1750 [3]. The resulting structure of the NPM reflects a synthesis of contemporary innovations and skilled craftsmanship, with contributions from renowned international artists commissioned for the project. While many of these crafted items have since vanished, the enduring legacy lies in the impressive structure constructed from locally sourced materials, which encapsulates the collective vision of architects, artists, engineers, craftsmen, and builders, under the leadership of the principal architect of King João V, German-trained in Rome: Johann Friedrich Ludwig, known as João Frederico Ludovice, who designed the winning Mafra project [6, 19]. His inspirations came from treatises by Alberti, Vitruvius, and Serlio [20], seventeenth-century buildings such as St Peter's Basilica (inspiration for the NPM Basilica) or Sant'Agnese church in Rome (inspiration for NPM church towers) [21], and Jesuit *modo nostro* principles [18]. The NPM's leading engineer was Custódio Vieira.

Functioning as the structural framework, the building's architecture serves as a canvas for artistic expression and daily life, facilitating the seamless integration of art and functionality. The NPM was built by approximately 45,000 workers, engineers, master builders, architects, and artists of French, Italian, German, Flemish, and Portuguese origin (who were also taught at the Mafra School of Sculpture and Masonry that developed at the NPM). The grandiose construction mobilised much of the kingdom's workforce. At times, over 15,000 workers were on site simultaneously, while little else was constructed in the kingdom. After completion, the workforce spread across Portugal, likely influencing eighteenth- and nineteenth-century architecture [6]. The NPM became a reference for later buildings [6, 22].

Stereotomic solutions in Mafra reflect eighteenth-century architectural achievements, although lack of existing construction drawings from the times the NPM was erected makes it impossible to verify with which accuracy plans and details were executed. In this paper, through the study and analysis of one example of vault we test a workflow to study stereotomy using advanced digital tools that will be later extended to all the main types of stereotomic solutions present in the NPM fabric.

Parametric modelling of historical buildings

Parametric modelling techniques represent a paradigm shift in historical building analysis and conservation. This study presents a unified method for architectural design and modelling, extending conventional CAD software with algorithmic-aided design (AAD). By leveraging computational tools, parametric modelling addresses complex challenges in heritage projects [23-24]. Techniques include photogrammetry, 3D laser scanning, Historical Building Information Modelling (HBIM), point cloud processing, and generative design algorithms [23-26], all crucial for capturing, analysing, and simulating historical building data, needed for informed decision-making throughout the conservation process [27-29].

Grasshopper, a visual programming language in McNeel Rhino 3D, is widely adopted in the architecture, engineering, and construction sectors for generating parametric models, that are a 3D reconstruction of existing objects, created with balanced degrees of accuracy and parametrisation [27].

Innovations such as machine learning, artificial intelligence, and virtual reality expand parametric modelling, enabling more accurate modelling, predictive analysis, and immersive visualisation of historical structures. Point cloud data can serve as libraries for Artificial Intelligence (AI) training, shape recognition, or 3D style transfer [30-31], supporting understanding of stereotomy and geometric characteristics of historical objects

Parametric modelling for heritage connects historians, architects, and computer scientists, requiring architectural, structural, geometric knowledge and basic programming skills, meaning professional toolkits must adapt to these new methods.

The documentary methodology

Preserving historical heritage is essential for safeguarding cultural identity and digitising it allows greater accessibility and understanding. Digital parametric models can also support exploration of forms, dissemination, videogames, 3D printing, and augmented or virtual reality [23]. However, our main focus is to develop a documentary methodology that, in its first phase, supports our study and understanding of stereotomic solutions using the NPM as our primary data source.

As a preliminary work, we defined a dictionary to name the different typologies of stereotomic elements detected in the NPM: stairs, arcs, vaults, domes. However, we found that it is not always possible to match existing terms in the literature with real elements. For example, none of the main names of vault types in the literature precisely matches the vault chosen as the first example to develop our documentary methodology.

Based on an inventory of the main stereotomic solutions present in the NPM, the methodology encompasses several phases for each element: i) surveying through laser scanning and/or photogrammetry; ii) preliminary analysis of the surveyed data to infer the geometric principles of the stereotomy; iii) generation of a parametric model of the visible surfaces of the vault; iv) analysis of the stone cutting and assembly.

To develop the methodology, we selected one vault located at the ground level under the left tower of the main façade of the NPM (Figure 1). It is a shallow, banded vault. It is a form that cannot be found in historical treatises, and since the original documentation is non-existent, the geometrical features of this element were unknown. It covers an area of approximately 5.9 × 5.9m. This vault was chosen because it is sufficiently complex to serve as the basis for deriving the documentary process, yet it is simple enough to allow rapid data acquisition and analysis. Once the methodology is validated, it will be applied to the full inventory.

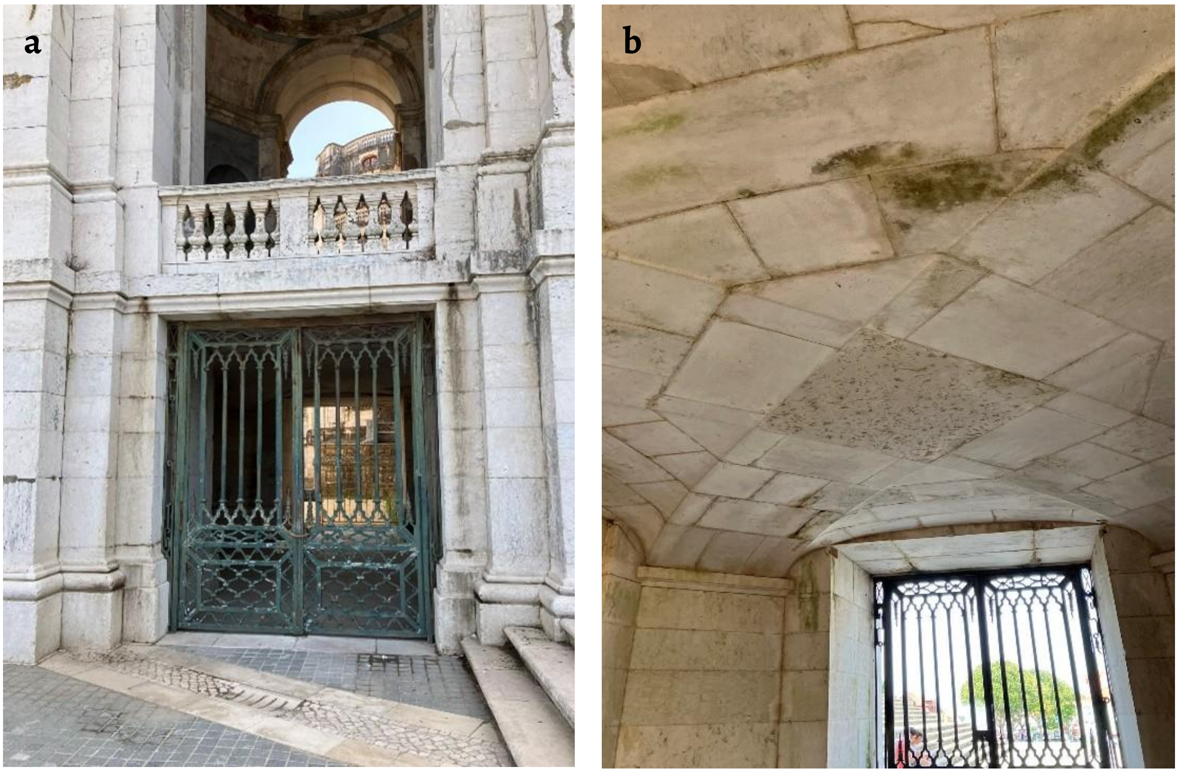

Figure 1. Vault: *a)* location of the vault in front facade; *b)* bottom view under the vault.

Surveying

Today, laser scanning and photogrammetry are considered standard methods for collecting accurate geospatial data. These tools can be used independently or together, depending on the object. For example, in a large building, laser scanning can capture overall geometry, while drone photogrammetry can record higher areas [8]. The initial concern is therefore selecting the appropriate surveying methods and tools.

We surveyed the chosen vault using a Faro Focus S120 laser scanner. A total of 16 scans was sufficient to cover the entire vault (Figure 2). Due to accessibility from the ground level and the absence of intricate details, scanning was straightforward. Since our focus is stereotomy, we did not document sculptural finishes, colours, or decorative details.

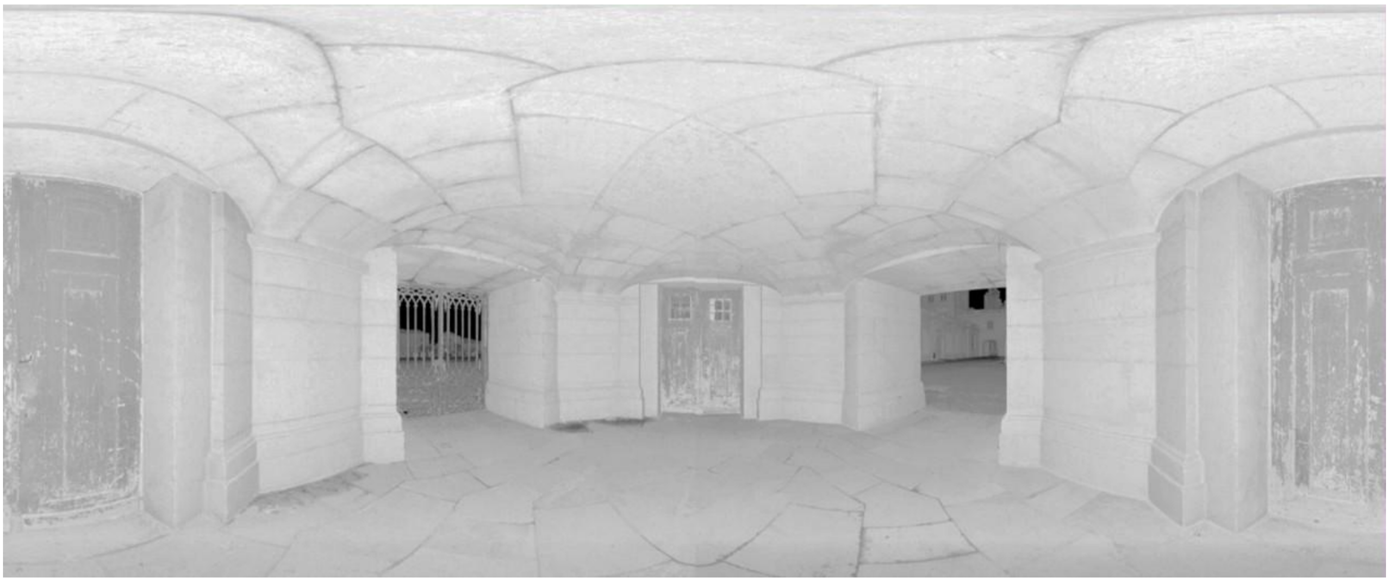

Figure 2. Panoramic view of the vault, obtained from laser scanning. It shows two openings (to the main façade of the palace and to the yard) and connections to interior of the palace.

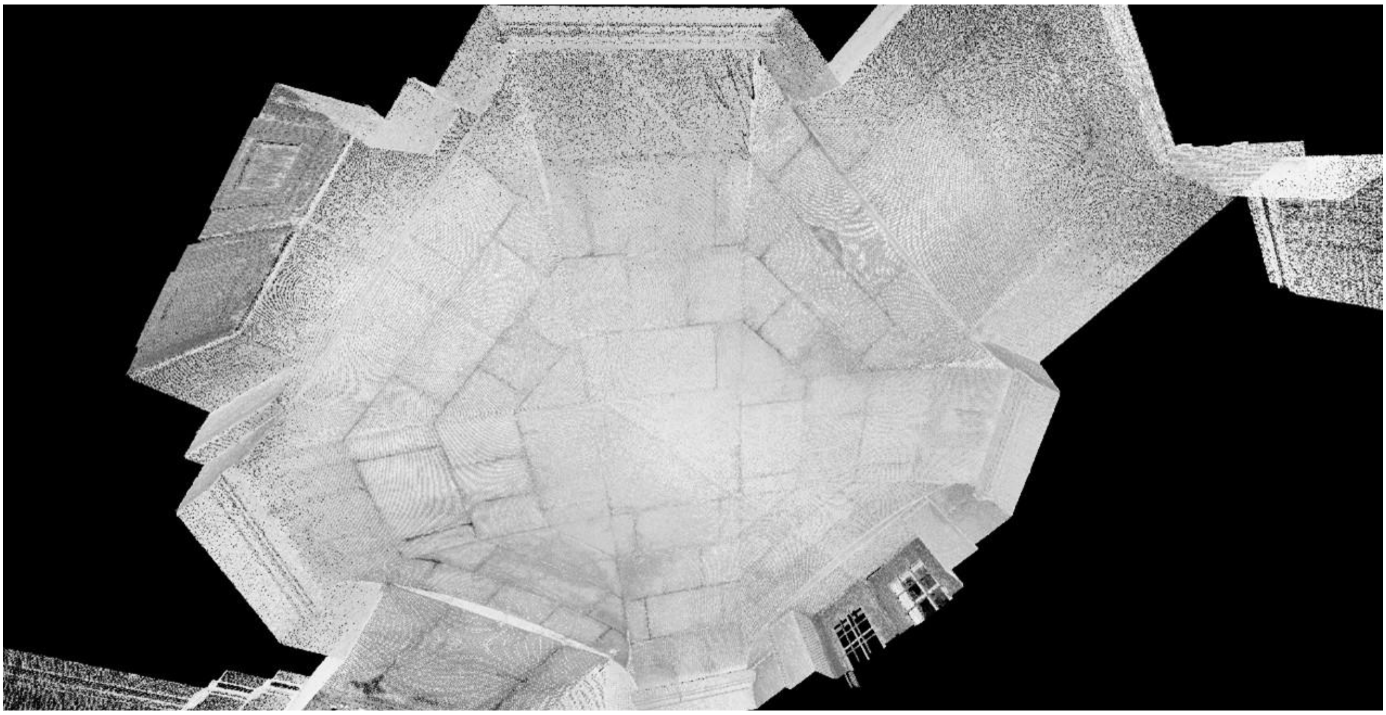

Figure 3. Point cloud of the vault viewed from bottom.

Point clouds were processed and aligned using Faro SCENE software, version 7.5. After processing, a sample containing the vault was exported (Figure 3).

Preliminary analysis

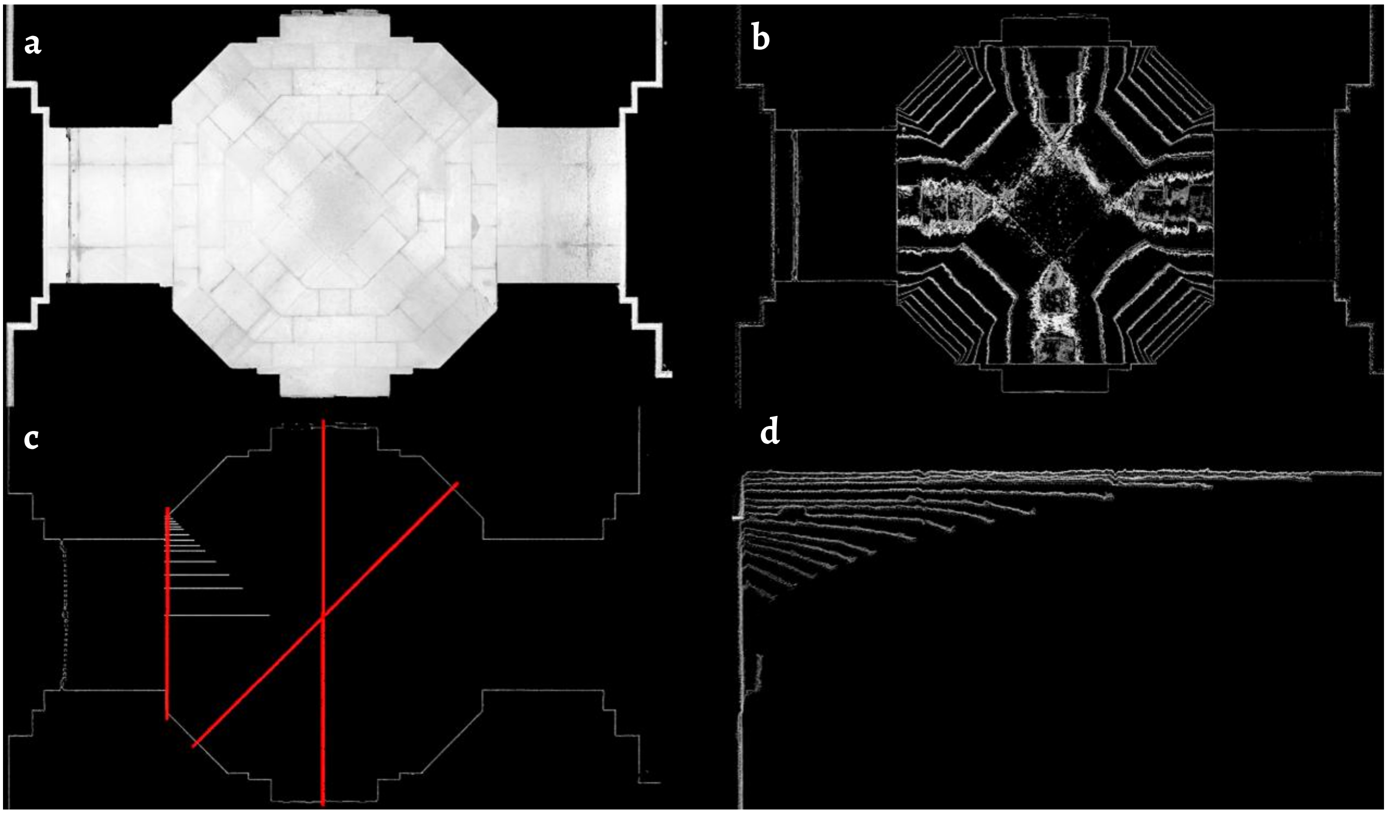

Figure 4. Point cloud of the intrados of the vault: *a)* top view to the intrados; *b)* series of horizontal sections; *c)* positions of main vertical sections marked in red; *d)* longitudinal section cuts showing that the main spans of the vault are not generated by extrusion.

Once we completed the alignment and obtained the final point cloud, we analysed it to infer the vault's geometric properties. To do this we extracted a series of horizontal, longitudinal, transversal, and diagonal sections (Figure 4). These sections will, later, allow us to make inferences about the geometric nature of the generating lines as well as the geometric nature of the surfaces.

Through a trial-and-error process, we searched for a match between the point cloud and different types of arcs. First, we tried with elliptical arcs in the main vertical sections but clearly there was not a good match. Then, it seemed possible to have a better match using chained circular arcs. This approach led us to experiment with different number of chained arcs which, in turn, suggested that the good fit could be obtained via oval arcs (Figure 5).

Manual modelling of the geometry based on the point cloud was meant as a base for understanding the crucial geometric properties of the vault, as its sections represented just fragments of the structure. It should be noted that a direct mesh modelling or NURBS modelling via spline lofting would not be the adequate approach although it could generate good representations of the vault. The reason is it would omit the geometric nature of the generating lines. On the other hand, it is known that the masons use physical gauges to orient the stone carving. So, the intention was to capture the geometric properties of those tools.

In this step, first the geometric properties of the generating lines are investigated. Then, it follows the study of how those lines are connected. This means, the study of the geometric surfaces that can be generated through those given lines. A visual inspection of the point cloud suggested that the vault was composed of ruled surfaces. Again, having the given point cloud data as reference, different methods to generate ruled surfaces were considered. Those include extruded surfaces, cylindroid surfaces and surfaces generated by a bundle of planes that meet at a given straight line.

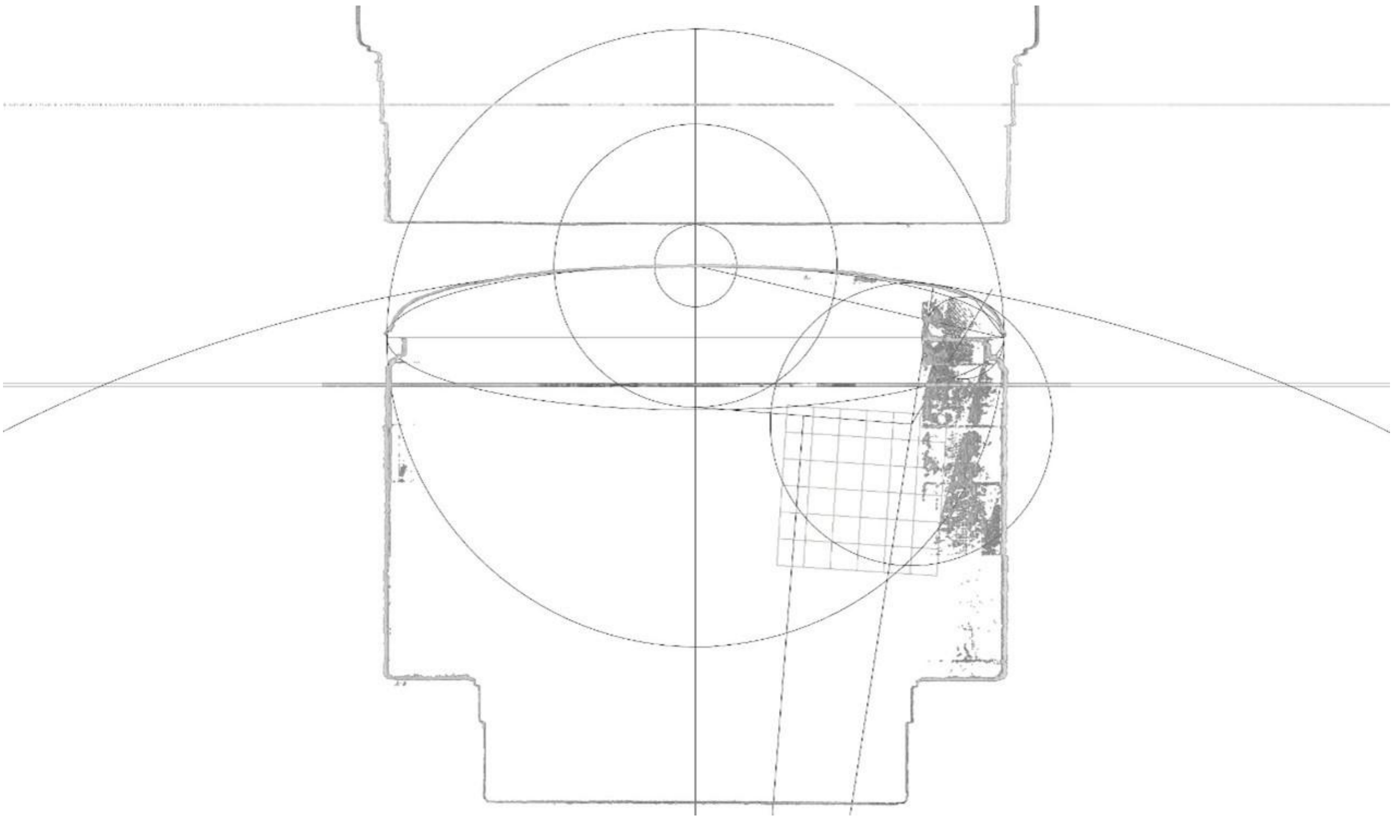

Figure 5. Trials of fitting arcs to the section of a point cloud.

Generation of a parametric 3D model

Connecting parametric modelling to heritage research allows us a flexibility of control over the model geometry. Recreating a vault with these tools enables us to deepen our understanding of the geometric principles behind its formation.

Generating a parametric model means that all the knowledge gathered up to this point can be incorporated into the generative process of the vault, extending its possibilities far beyond the generation of the specific vault studied so far. This means that the parametric model can generate not only this vault but also a multitude of other vaults that share common principles with it.

The first step in the definition of the parametric model is to set up dimensional constraints or parameters (Figure 6).

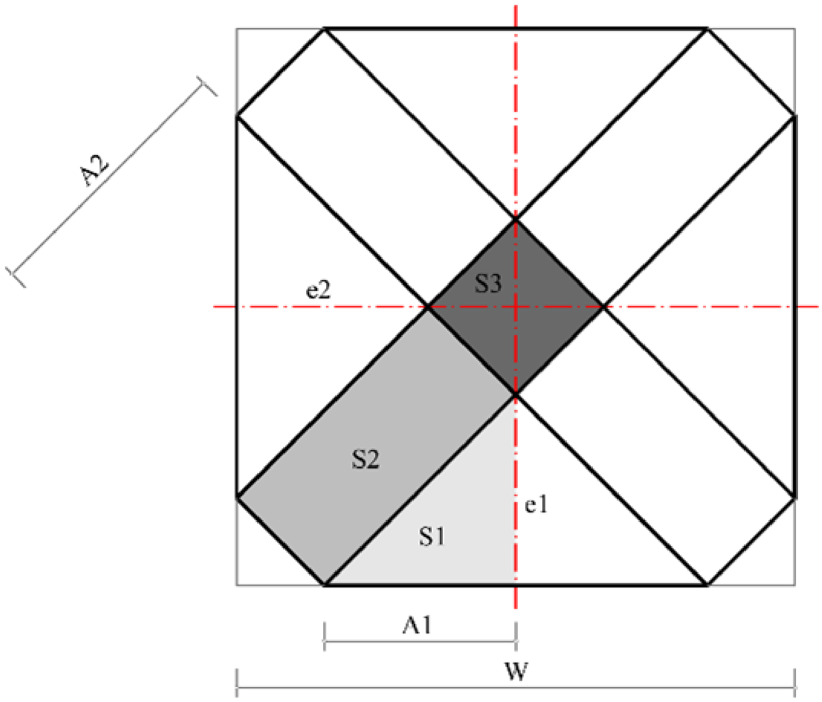

Figure 6. The main parameters of the vault, in top view. The vault has not only 4 bays, but also X-shaped bands that cross it, that require additional input parameters to control them.

The first parameter to be set is the square shape of the top view and its width, W. Then the symmetry axes e1 and e2 mean that only a quarter of the vault needs to be generated, and the other parts can be obtained via mirror and/or polar array operations.

The shaded areas correspond to the different surfaces that need to be generated. In light grey we have a surface, S1, that subtends two half arcs, A1 and A2. In medium grey, an extrusion surface, S2, obtained from arc 2 (A2). In dark grey, a planar square surface, S3, in the top of the vault.

Following the preliminary analysis of arc A1, it became apparent that the best solution to fit the studied vault would be a seven-centre oval arc. However, in the parametric model we included circular arc, elliptical arc, segmented arc, three centre oval arc, five centre oval arc and seven centre oval arc as options that the user can pick (Figure 7). The insertion of the arcs into the algorithm means adding a new parameter, the distance [HC] in Figure 7, or height of arc 1.

The assumptions used to generate surface S1 determine the nature of arc 2. If surface S1 is generated through an extrusion of arc 1 along edge 1, then arc 2 is the result of the intersection of the extruded surface with the vertical diagonal plane of arc 2. We named this method as Front Arc Based. This was the first method used to generate surface S1, but it did not provide a good result when compared to the real data.

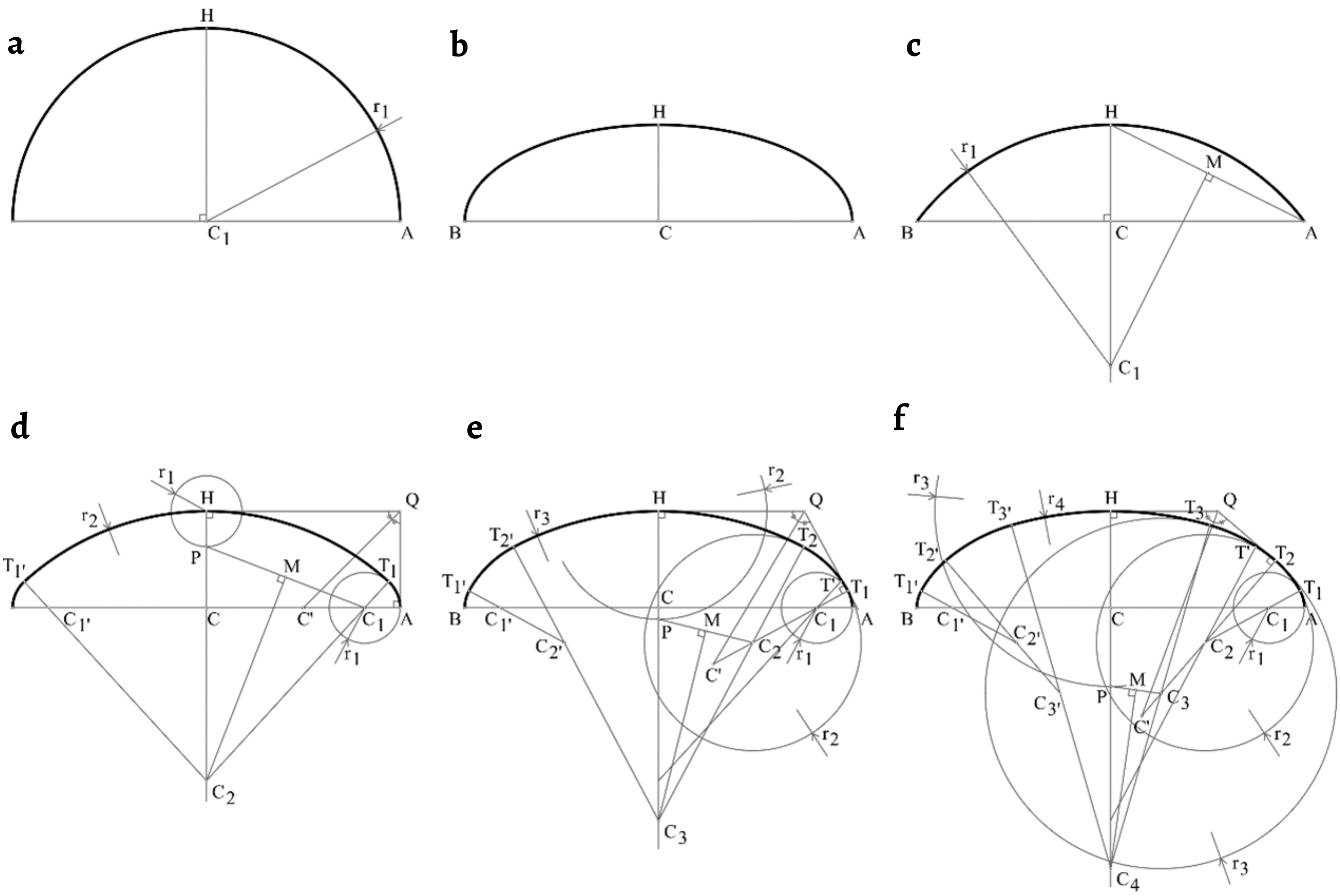

Figure 7. Parametrical model: *a)* circular arc; *b)* elliptical arc; *c)* segmented arc; *d)* three centre oval arc; *e)* five centre oval arc; *f)* seven centre oval arc.

If surface S1 is generated through an extrusion of arc 2 along edge 1, then arc 1 is the result of the intersection of the extruded surface with the vertical plane that passes through the side of the circumscribed square. We named this method as Diagonal Arc Based.

Another method was considered. In this method, arc 1 and arc 2 are considered independent and with the same height [HC] (Figure 7), unless semicircular arcs are used. In that case, [HC] corresponds to the radii of the circles. In turn, this method considers two possible ways to generate ruled surfaces connecting the arcs 1 and 2. The first one uses a bundle of planes parallel to the vertical plane passing through edge 1. The other one uses a bundle of planes that pass through a straight line, not necessarily horizontal, lying in the vertical plane of edge 1. These planes intersect both arcs in points connected with straight lines.

To summarize, the three methods used to generate surface S1 are: i) extrusion of arc 1 along edge 1 - Front Arc Based (Figure 8a); ii), extrusion of arc 2 along edge 1 - Diagonal Arc Based (Figure 8b); iii) bundle of planes - Double Arc Based (Figure 8c).

The output of the parametric model is a BREP (boundary representation) that can be further converted to other representations like meshes or stereolithography (STL).

Since the parametric model allows us to generate very wide variety of vaults (Figure 8), the metadata for each one must be saved to keep a record of the process. This is important for recreation of the solution. Essentially, metadata include a list of the parameters used in the vault generation, some metric properties like area, and other data like file name. The implementation of the parametric model was done using the Rhino/Grasshopper modelling environment.

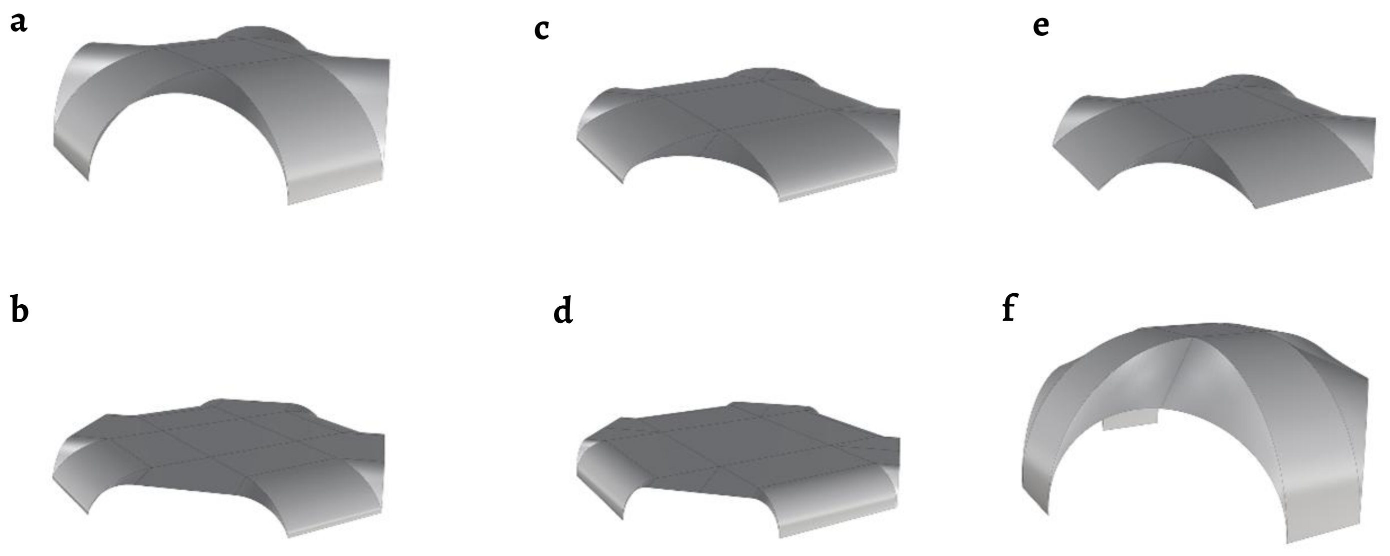

Figure 8. Examples of solutions thanks to parametric vault model: Front arc based: *a)* circular arch and *b)* 7 center arch; Diagonal arc based: *c)* elliptical arch and *d)* 7 center arch; Double arc based: *e)* front arch – 3 center arch , diagonal arch – segmented arch and *f)* front arch – circular arch , diagonal arch – circular arch.

Fitting the model to real data

As the parametric model was developed, an iterative process was followed. It implicated that, for each hypothesis about the nature of an arc or surface, a fitting approach to the point cloud was conducted. The best fit was achieved through a double arc approach where both arcs were seven centre oval arcs. The surface S1 was ruled and generated through a bundle of oblique planes passing to a line parallel to axis e1 (Figure 6). To validate the model, the BREP representation of the vault was converted into a mesh saved in STL. Then a distance analysis between the surveyed point cloud and the mesh to analyse the final model deviation was performed (Figure 9).

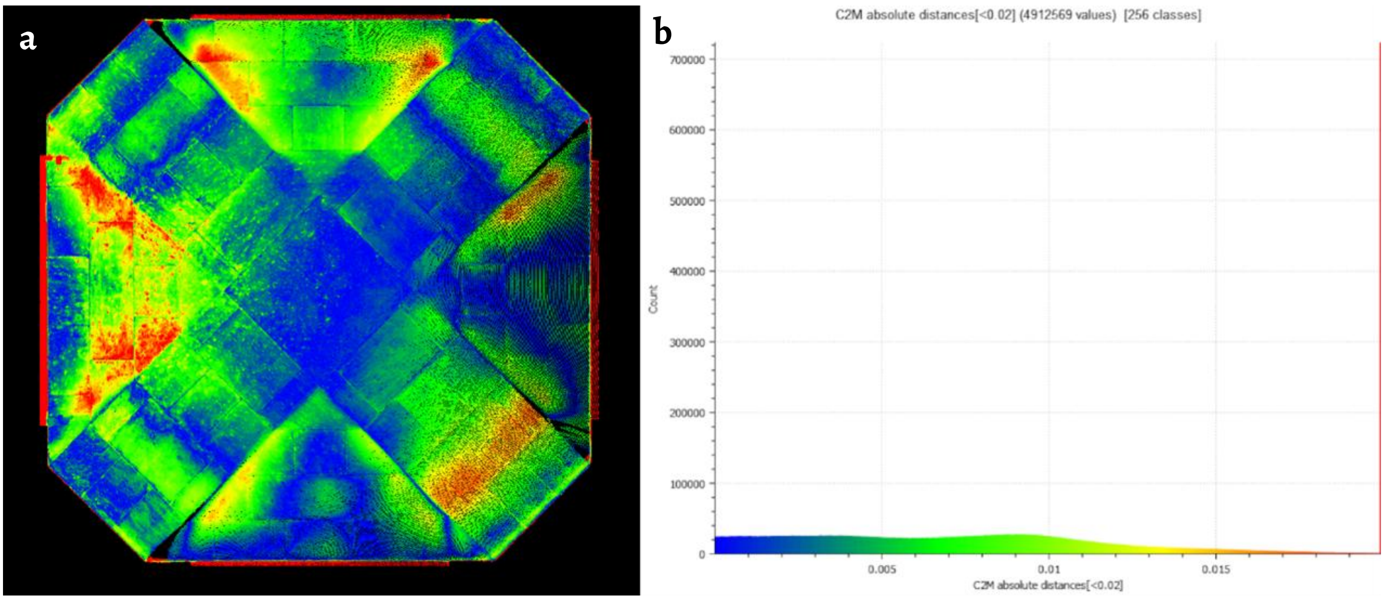

Figure 9. Distance analysis between developed mesh and the point cloud (a) shows minimal deviation between the parametrically developed surface and the real data, less than 1 cm (b).

From Figure 9 it can be seen that the overall mesh-to-point cloud distance is less than 1 cm. For the purposes of this research, we consider that this distance analysis is a form of validation of the model generated. The differences can be explained by small inaccuracies during the construction and small deformations during time. The result is quite impressive if we consider that the parametric model is an ideal geometric model.

Analysis of the stone cutting and assembly

The point cloud provides an accurate representation of the visible parts of joints of the ashlars that constitute the vault. That information allows us to model a hypothesis of the assembly of the stones that form the structure as it can be seen in Figure 10.

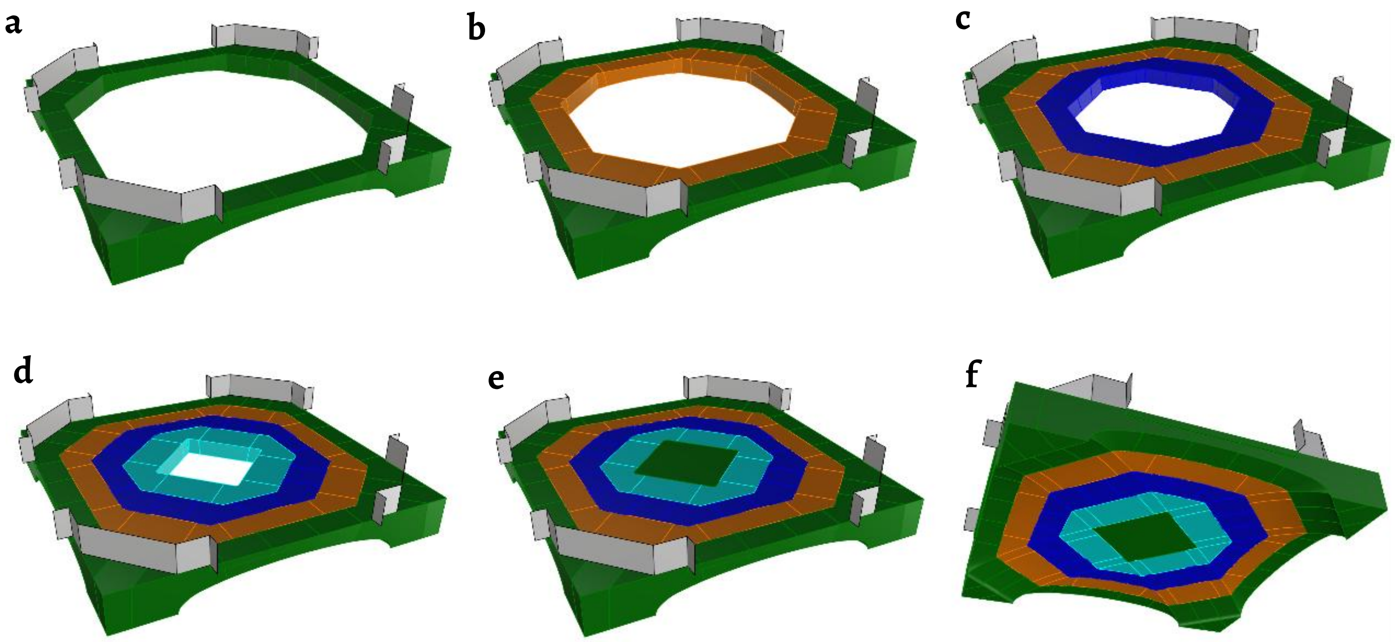

Figure 10. Modelling of the ashlars ring by ring: *a)* first row; *b)* second row added; c) third row added; *d)* fourth row added; *e)* closing ashlar added; *f)* bottom view of the intrados.

We call it a hypothesis because point clouds only provide us data about the visible surfaces. No record of the interface surfaces of the ashlars is available, therefore, although informed, the model does not have 100 % certainty. In fact, its analysis raises interesting questions. The first row of ashlars shows a typical arc structure replicated four times (Figure 10a). But an interesting issue appears between the first and second rows (Figure 10b). The interface surface between these rows appears to be vertical as the joints in the bottom of the vault and the corresponding ones in the upper pavement are vertically aligned. Of course, that is structurally impossible because, it would mean that no arc behaviour exists. The logical consequence is that the second row of ashlars would not stand. But in reality, it holds, which means that some extra cutting geometry, not visible, had to have been implemented. In our model we assumed a geometric configuration of the corner ashlars of first row that enables an arc behaviour (Figure 11). However, to understand what is really happening, other recording tools would need to be employed.

Then, for the remainder of the rows (Figure 10c-e), the joints of the ashlars ensure that the vault structurally works as they are not vertically aligned. In Figure 10f we have a bottom perspective of the modelled vault.

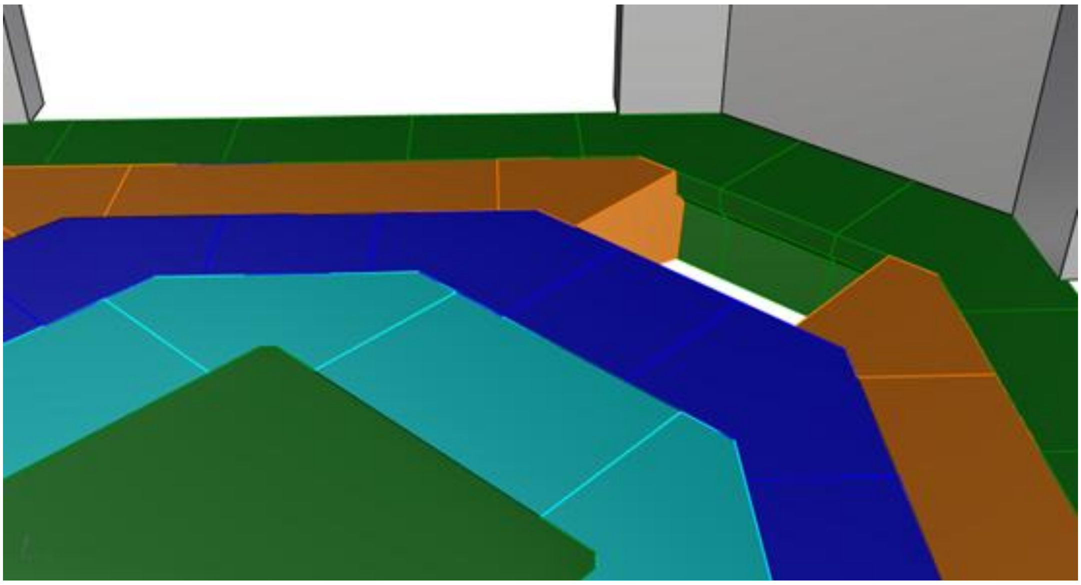

Figure 11. Perspective view of the assembly with one ashlar removed to make the joint between first and second row visible.

Conclusions and future research

Understanding stereotomy is important because it is one of the main methods of constructing most of monumental Portuguese architectural heritage from the eighteenth century. Looking back to earthquake that destroyed most of Lisbon central area in the same century it is valid to have in mind possible natural disasters, that may damage or destroy buildings being a vital part of national history and identity. This research shows in depth geometrical analysis of an exemplary element, vault, and can be scaled up to other instances and different heritage buildings, since it is possible to track style influences of the eighteenth century in Portugal. Creating parametric models of the vaults allows precise fit and geometrical analysis which is valuable for historical/constructive analysis and to support conservation and restoration actions.

So far, we have developed a documentary methodology to record and analyse stereotomic constructive elements from a geometrical point of view. Since the methodology includes the development of parametric models, besides allowing the precise representation of real stereotomic elements, it also allows the generation of a multitude of other models that, somehow, are from the same family as the real ones. This way we can instantiate virtually a limitless number of exemplars of vaults.

As future research, we will develop a tool to generate synthetic point clouds from the parametric models. These point clouds can be used as a base for training of artificial intelligence tools that can be helpful to optimize the surveying process or to allow contemporary designs through 3D style transfer algorithms. This means that we have potential to further explore those models and even use them as inspiration for contemporary designs.

The stone cutting process also raises interesting questions that were not analysed in this paper. These, together with structural simulations is another possible path for future research.

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REFERENCES

1. *Royal Building of Mafra: nomination for inscription on the World Heritage List*, General Directorate of Cultural Heritage - Municipality of Mafra, Lisboa (2017).
2. Callabria, C., *Construction and compositions of the 16th century multi ribbed vault in Portugal: conceptual transposition in the contemporary project*, Polytechnic School of Bari, Bari (2015).
3. Calvo-López, J., *Stereotomy: stone construction and geometry in Western Europe, 1200-1900*, Birkhäuser, Cham (2020), https://doi.org/10.1007/978-3-030-43218-8.
4. Genin, S., "The vaults of Arronches Nossa Senhora da Assunção and Misericórdia churches. Geometric and constructive comparison with the nave and refectory vaults of Jerónimos Monastery', in *Thinking, drawing, modelling*, eds. V. Vina, V. Murtinho & J. P. Xavier, Springer International Publishing, Berlin (2020) 66-75.
5. Pereira, P.; Bonifácio, H.; Gorjão, S.; Duarte, J.; Vale, T. L., *Do tratado à obra: génese da arte e arquitetura no Palácio de Mafra*, Direção Geral do Património Cultural, Lisboa (2017).
6. Mateus, L.; Brito, N.; Ferreira, V.; Barbosa, M.; Aguiar, J., 'New tools for visual assessment of building deformations', in *8th International conference on Structural analysis of historical constructions*, Wiley Online Library, Hoboken (2012) 2463-2470, https://doi.org/10.1002/stab.201290150.
7. Mateus, L.; Fernández, J.; Ferreira, V.; Oliveira, C.; Aguiar, J.; Gago, A. S.; Pacheco, P.; Pernão, J., 'Graphical data flow based in tls and photogrammetry for consolidation studies of historical sites: the case study of Juromenha Fortress in Portugal', in *ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLII-2/W15** (2019) 767-773, https://doi.org/10.5194/isprs-archives-XLII-2-W15-767-2019.
8. Derand, F., *L' Architecture des Voutes, ou L'art des Traits, et coupe des voutes: Traicté tres-util, voire necessaire a tous architectes, maistres massons, appareilleurs, tailleurs de pierre, et generalement a tous ceux qui se meslent de l'architecture, mesme militaire*, Sebastien Cramoisy, imprimeur ordinaire du Roy, Paris (1643).
9. Desargues, G.; Bosse, A., *La Pratique du Trait a preuues de Mr Desargues pour la Coupe des pierres en L'architecture*, Pierre Des-Hayes, Paris (1643).
10. Frézier, A.-F., *La theorie et la pratique de la coupe des pierres et des bois pour la construction des voutes et autres parties des Bâtimens Civils & Militaires, ou Traité de Stereotomie a l'usage de l'Architecture*, vol 3, Charles-Antoine Jombert Libraire, Paris (1739).
11. La Hire, P., *Traité de la coupe des pierres*, Bibliothèque de l'Ecole Nationale des Ponts et Chaussées, Paris (1688).
12. Vandelvira, A., *Libro de trazas de cortes de piedras*, Biblioteca de la Escuela de Arquitectura de la Universidad Politécnica de Madrid, Madrid (1585).
13. Delgado, R., *A geometria na estereotomia da pedra na arquitectura religiosa portuguesa entre 1530 e 1580*, PhD dissertation, Faculdade de Belas-Artes da Universidade de Lisboa, Universidade de Lisboa, Lisboa (2017).
14. Genin, S.; De Jonge, K.; Gonzalo Palacios, J. C., 'Portuguese vaulting systems at the dawn of the early modern period: between tradition and innovation', in *Proceedings of the third international congress on construction history*, eds. W. Lorenz, V. Wetzk, & K.-E. Kurrer, Brandenburg University of Technology, Cottbus (2009) 671-678.
15. Saramago, J., *Baltazar i Blimunda*, Rebis, Poznań (2012).
16. *Executive summary of the nomination 1573, Royal Building of Mafra - Palace, Basilica, Convent, Cerco Garden and Hunting Park (Tapada)*, General Directorate for Cultural Heritage, Lisboa (2019).
17. *Royal Building of Mafra - Palace, Basilica, Convent, Cerco Garden and Hunting Park (Tapada)*, ICOMOS, Paris (2019), https://whc.unesco.org/en/list/1573 (accessed 2024-06-17).
18. Russell-Wood, A. J. R., 'Portugal and the World in the Age of D. João V', in *The art of the Baroque in Portugal*, ed. J. A. Levenson, National Gallery of Art - Yale University Press, Washington D.C. -New Haven (1993) 15-30.
19. Duarte, E., 'Da França à Baixa, com passagem por Mafra: as influências francesas na arquitectura civil pombalina', *Monumentos* **21** (2004) 76-87.
20. Delaforce, A., '«This New Rome»: Dom João V of Portugal and relations between Rome and Lisbon', in *The age of the Baroque in Portugal*, ed. J. A. Levenson, National Gallery of Art - Yale University Press, Washington D.C. -New Haven (1993) 49-79.
21. Gil, J., *As mais belas Igrejas de Portugal*, vol. II, Verbo, Lisboa (1989).
22. Moyano, J.; Carreño, E.; Nieto-Julián, J. E.; Gil-Arizón, I.; Bruno, S., 'Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project', *Automation in Construction* **143** (2022) 104551, https://doi.org/10.1016/j.autcon.2022.104551.
23. Liberotti, R.; Gusella, V., 'Parametric modeling and heritage: a design process sustainable for restoration', *Sustainability (Switzerland)* **15**(2) (2023) 1371, https://doi.org/10.3390/su15021371.
24. Mateus, L.; Ferreira, V.; Aguiar, J.; Pacheco, P.; Ferreira, J.; Mendes, C.; Silva, A., 'The role of 3D documentation for restoration interventions: the case study of valflores in Loures, Portugal', *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* **54**(M–1) (2020) 381-388, https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-381-2020.
25. Jozef, L.; Oostwegel, N.; Jaud, Š.; Muhič, S.; Rebec, K. M., 'Digitalization of culturally significant buildings: Ensuring high - quality data exchanges in the heritage domain using OpenBIM', *Heritage Science* **10** (2022) 10, https://doi.org/10.1186/s40494-021-00640-y.
26. Sousa, M. O.; Correa, F. R., 'Towards digital twins for heritage buildings: a workflow proposal', *International Journal of Architectural Computing* **21**(4) (2023) 712-729, https://doi.org/10.1177/14780771231168226.

27. Historic England, '3D laser scanning for heritage', *Advice and guidance on the use of laser scanning in archaeology and architecture*, Historic England, Swindon United Kingdom (2018) 1-113, https://historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage/heag155-3d-laser-scanning (accessed 2024-06-21).
28. Hull, J.; Bryan, P., *BIM for heritage: developing the asset information model*, Historic England, London (2019), https://bit.ly/3fIqn9s (accessed 2024-06-21).
29. Zhang, H.; Blasetti, E., '3D architectural form style transfer through machine learning', *RE: Anthropocene, Design in the Age of Humans - Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2020* **2** (2020) 661-670, https://doi.org/10.13140/RG.2.2.16791.52645.
30. Cao, X.; Wang, W.; Nagao, K.; Nakamura, R., 'PSNet: a style transfer network for point cloud stylization on geometry and color', in *Proceedings - 2020 IEEE Winter conference on applications of computer vision, WACV 2020* (2020), https://doi.org/10.1109/WACV45572.2020.9093513.
31. García-Fernández, J.; Mateus, L., 'Solution supporting the communication of the built heritage: semi-automatic production path to transfer semantic LIDAR data to minecraft environment', *Digital Applications in Archaeology and Cultural Heritage* **14** (2019), https://doi.org/10.1016/j.daach.2019.e00112.

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