The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023
29th CIPA Symposium "Documenting, Understanding, Preserving Cultural Heritage:
Humanities and Digital Technologies for Shaping the Future", 25–30 June 2023, Florence, Italy

KNOWLEDGE-BASED MODELLING FOR AUTOMATIZING HBIM OBJECTS. THE VAULTED CEILINGS OF PALAZZO DUCALE IN URBINO

Ramona Quattrini[1], Giulio L. S. Sacco[2], Giorgia De Angelis[1], Carlo Battini[2]

[1] Dept. of Construction, Civil Engineering and Architecture (DICEA) - Università Politecnica delle Marche - Ancona, Italy.
[2] Dept. of Civil, Chemical and Environmental Engineering (DICCA) - University of Genoa - Genoa, Italy.

KEY WORDS: HBIM, ontology, vaults, digital modelling, scan-to-BIM, semantic modelling, shape grammar, geometrical rules

ABSTRACT:

Vault modelling in HBIM poses a significant challenge due to the geometrical complexity and lack of standardization of those elements. Starting from the definition of an ontology able to describe and manage different typologies of Italian Renaissance vaults, this paper presents two methods for their representation in the context of Ducal Palace of Urbino HBIM implementation. The first method is a simplified semi-automated scan-to-BIM procedure relying on Revit adaptive families; the second is a more complex parametric scripting in Dynamo VPL. The paper proposes a library of suitable vault families for the parametric modelling of Renaissance architecture and offers a comparison between the models generated and their respective surveyed point-clouds, with the aim of assessing the procedure. Revit adaptive families appeared to be the easiest to implement and the most efficient solution, while Dynamo allowed for greatest complexity thought showing limitations and implementation difficulties.

1. INTRODUCTION

The technological tools of BIM have been developed with the aim of designing and assembling the building components according to seriality and repetition principles, coming from the industrial sector. Seriality, repetition, and standardization can rarely be found in historical buildings, since they are the unique product of artisanal work. While BIM families for new building are usually enough to cover most needs, and are often made easily available to the designers directly by the manufacturers working in the construction industry, the same is still not true for HBIM where parametric families are missing or inadequate even for common recurring elements. For historical buildings most of the objects still need to be realized "ad hoc" trying to obtain libraries of families of recurrent elements based on proportions and widely used geometric rules. Even in these unique and unrepeatable objects, in fact, there are geometric and proportional patterns that can be parameterized.

Most of the standard BIM tools and methodologies can be applied in HBIM but the lack of specialized tools for the translation from the survey to the model (i.e. scan-to-BIM processes) represents a huge limitation in the industry. In this context, a synthetic description of elements geometry is usually the best solution and is also enough to carry the information needed to properly describe the architecture, especially when the knowledge of the building is not complete as it commonly happens with cultural heritage. In those cases, the use of generalized adaptive families can be proficient because it can deliver synthetic geometries with suitable accuracy for the task and can meet target LOD, with reduced costs in term of time and effort. In this framework, the implementation of scan-to-BIM procedures is the obvious approach to obtain reliable results in the modelling phase, while assuring geometrical accuracy.

The importance of semantically rich representation of the architecture, which takes into account the relationship amongst the different elements of a building and requires an object-based parametric modelling approach, is the driver of the current research in the field.

This paper presents two approaches for the parametric representation of vaults in HBIM environment in the context of the implementation of Urbino's Ducal Palace BIM. A simplified semi-automated scan-to-BIM procedure was developed in Revit relying on adaptive families, while another more complex and highly adaptable parametric scripting was implemented in Dynamo Visual Programming Language (VPL). The two methodologies were tested modelling recurring vaults of Italian renaissance also present in the ceiling of the main floor of the Ducal Palace. The methodology used to generate the vaults was extensively explained and a quality assessment of the geometrical model produced for the Ducal Palace ceiling was performed in the more complex case of the VPL approach.

2. STATE OF THE ART

The purpose of BIM methodology is to support the management of buildings during their lifecycle through the use of a database of well-organized and meaningful information linked to the geometry of the individual constitutive elements. The geometrical representation accuracy needed is directly linked to the quality and quantity of the information that the single elements must carry, and different libraries of parametrical element are used to generate these geometries. This concept is incorporated in the use of different levels of development (LODs) during the design process, according to the UNI 11337 standard. From the lower LOD of the pre-design stage to the highest one which represents the actual as-built representation of the building and carries all the information available, the LOG (level of geometry) and LOI (level of information) usually increase at the same time.

In HBIM the implementation of the model starts from the survey and the study of an existing building and therefore LOD cannot represent a linear sequence of design advancement but can be used to represent the different levels of knowledge reached for different elements of the building in regard with the conservation needs (Brumana, et al., 2018).

Nowadays, many existing buildings have insufficient or no documentation and therefore an as-built BIM model must usually be created from scratch. Since the definition of HBIM methodologies (Murphy, McGovern, & Pavia, 2009), point cloud data obtained from laser scanning or photogrammetric techniques are the basis for the reconstruction of existing structure through scan-to-BIM procedures (Volk, Stengel, & Schultmann, 2014) and, if properly used, they allow for extremely accurate models of high LOG that can easily be disproportionate to the available LOI that's commonly affected by numerous uncertainties. Even if an accurate and detailed geometrical representation of a building could allow for a more punctual localization of specific

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1271-2023 | © Author(s) 2023. CC BY 4.0 License.

information, it could reveal itself to be resource consuming and not rewarding for practical purposes. More importantly, when geometrical accuracy is achieved employing local objects, it's directly against the BIM principles of abstraction, parametrization and definition of meaningful relationships with other objects in the model (Argiolas, Cazzani, Reccia, & Bagnolo, 2019). Therefore, a proper implementation of an HBIM model should always aim to a balance between geometrical accuracy, abstraction, and proper representation of the single building singularities (Banfi, 2019) (Moreira, Quattrini, Maggiolo, & Mammoli, 2018). In this context, the scan-to-HBIM method requires adapting the definition of LOGs to the different phases that characterises the heritage preservation and management, reversing the new construction logic based on simple-to-complex informative models. A possible approach (Brumana, Stanga, & Banfi, 2022) proposes to apply the well-known concept of scale to the object model generation, defining different Grades of Accuracy (GOA). A vast literature was produced in this regard, as a matter of fact it is possible to rely on different surveys about HBIM (e.g. (López, Lerones, Llamas, Gómez-García-Bermejo, & Zalama, 2018).

Semantic segmentation of 3D Point Clouds is gaining more and more attention, since it might help to automatically recognize historical architectural elements and consequently could be a turning point in automatizing or, at least, deeply changing the scan-to-BIM process. In this regard, robust results for historical heritage are shown by Machine Learning (Grilli & Remondino, 2019) (Teruggi, Grilli, Russo, Fassi, & Remondino, 2020), when annotated data are useful to streamline the construction of H-BIM systems, where purely geometric information derived from surveying is associated with semantic descriptors on heritage documentation and management (Croce, et al., 2021). In addition, the way paved by recent Deep Learning approaches proved to be reliable in other contexts and opened up new research opportunities, together with the evolution of deep learning methods in processing 3D data, such as 3D point cloud classification for object identification and semantic annotation (Pierdicca, et al., 2020) (Marissia, et al., 2021). In order to have sufficiently rich databases, also the data augmentation is a lively field of experimentation in which synthetic datasets are created to tackle the scarcity of labelled point cloud data (Jing, Sheil, & Acikgoz, 2022) (Morbidoni, Perdicca, Paolanti, Quattrini, & Mammoli, 2020). The experimentations are still relevant not only for the historical heritage (Zhai, Zou, He, & Meng, 2022).

Vaults have been a fundamental theme in European architectural culture and, therefore, they are commonly found in heritage buildings. Despite this, vaults are one of the least resolved topics in HBIM, both due to their geometrical complexity and lack of standardization if compared, as an example, with classical orders elements. There is plenty of literature on vaults modelling from point clouds mostly in HBIM and numerical modelling fields (i.e. FEM) and several attempts have been made to define modelling methodologies able to fulfil different needs.

In HBIM framework, with a scan-to-BIM approach, both local models and parametric families were used. Despite local modelling was frequently used in literature (Fiorillo, Rossi, & Morandi, 2021) (Brumana, Condoleo, Grimoldi, & Landi, 2017), research interests moved to the definition of parametric models able to produce synthetic vaults with different approaches. Attempts were made in order to define reusable families based on historical treatises and local constructive praxis through the combination of VPL and BIM tools. Spallone and Calvano (Spallone & Calvano, Parametric Experiments on Palladio's 5 by 3 Villas, 2022) developed instruments to interpret and create 3D parametric models of Palladio's villas starting from *I Quattro libri dell'architettura* as a primary source; Capone and Lanzara (Capone & Lanzara, 2019) compared drawing rules provided by different authors for Campanian historical vaults and implemented those rules for new vaults families. Some authors offer an in deep analysis and a modelling procedure with high LOD and Log, able to describe constructive features and map 3Dmensionally each brick (Attico, et al., 2019). Other approaches opted for the extraction of geometrical features directly from the point cloud, proceeding to the model generation with no further hypothesis other than the vault typology (Bagnolo & Argiolas, 2021).

BIM parametrization capabilities was also exploited to generate models for structural analysis. A complete automated method for the generation of ribbed masonry vaults from point clouds is presented in (Angjeliu, Cardani, & Coronelli, 2019). The LOG and the high segmentation achieved in the study was needed to carry structural analysis but it's not commonly viable to reach such a degree of knowledge about cultural heritage.

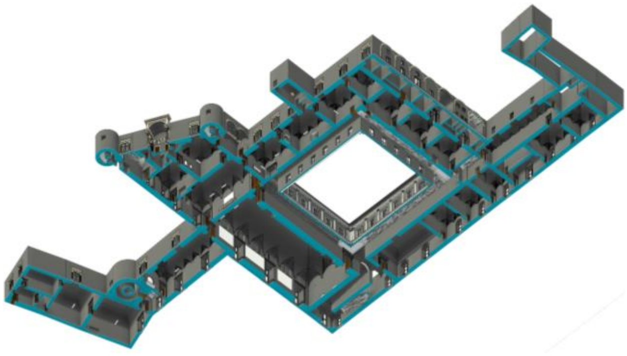

Figure 1: Portion of the Ducal Palace HBIM model in Revit environment. Axonometric view of the main floor and vaulted

3. PURPOSES

The aim of this paper is to address the topic of vaults representation in a HBIM environment: starting from the definition of an ontology able to describe and manage different typologies of Italian Renaissance vaults (i.e. barrel vaults, groin vaults, cloister vaults, mirror vaults, etc.), then focusing on their generalization and parametrization, up to the geometrical modelling and data enrichment. With a focus on the geometrical modelling, two different approaches to semi automate the cloud-to-BIM process are presented from the data analysis to the definition of adaptive families in Revit and Dynamo. A parametric approach was adopted trying to fulfil a purpose of reusability and to close the gap between the implementation of a BIM model for a new building and the implementation ad a HBIM one. The first approach was used for simpler vaults (i.e. barrel, cross and mirror vaults) and consisted in the implementation of adaptive families in Revit, while the second approach, used mainly for the pavilion head lunette vaults, used VPL in Dynamo.

In the context of the Strategic Project CIVITAS (Chain of Excellence of Reflective Societies exploit the digital cultural heritage and museums) directed by Università Politecnica delle Marche (Clini, et al., 2020), the developed methodologies were applied and tested in the HBIM implementation of the first floor (main floor) of the Urbino Ducal Palace (Figure 1). Lastly, a quality assessment by the means of deviation analysis was performed on three most significant vaults of the Ducal Palace to prove the reliability of the VPL approach.

4. METHODOLOGY

In heritage buildings, the different elements are linked together by geometrical rules and proportional patterns that are the base

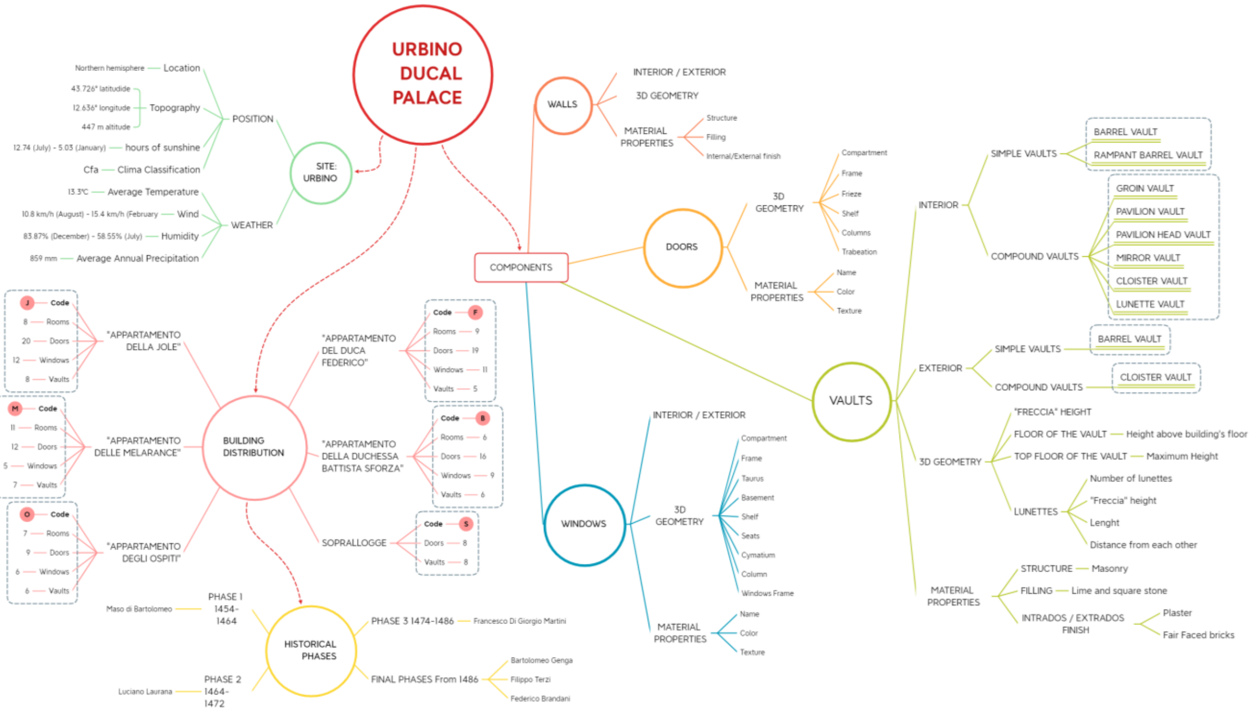

Figure 2: Graphical representation of the ontology developed during the HBIM implementation of the Urbino Ducal Palace

of architectural language and can be generalized and parametrized. Recurring elements of historic architecture have been studied for centuries and the mathematical and proportional rules that regulate the relationship amongst those elements were codified since Vitruvius's work. The historical rules and their implications in the area of the 3D modelling stands from the Stiny & Mitchell approach (Stiny & Mitchell, 1978) . More recently, the historical corpus of this knowledges shows a sort of "algorithmic thinking" of ancient architecture (Aubin, 2013) that can be easily translated into actual algorithms in modern BIM software, to define all the families that assembled together can define a semantically rich HBIM model. A key point is in addition is surely the semantic intelligence (Apollonio, Gaiani, & Sun, 2017), that has to be clearly identified and properly managed when dealing with HBIM procedures.

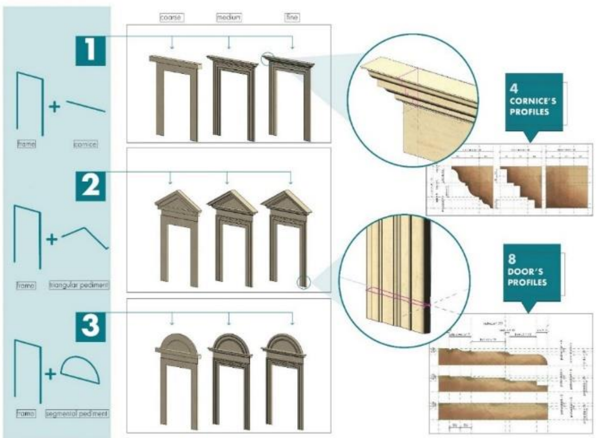

Figure 3: Examples of the combination of source families to generate the same architectural elements in three different levels of detail.

To define an unambiguous reference system able to organize the knowledge domain related to the Ducal Palace and to provide a shared vocabulary, an ontology comprehensive of all the architectural elements (i.e. walls, windows, mouldings, decoration, etc.) was developed (Figure 4).
The result was an accurate taxonomic description of those elements coinciding with related Revit families that have been later implemented following different strategies.
At first, walls were organized in an abacus and then the fourteen different typologies observed on the point-cloud were translated into two families (i.e. brick masonry and rubble-filled masonry) according to the stratigraphic information derived from literature (Polichetti, 1985) (Bardi, 1706). Similarly, the forty-five windows with the typical stone seats and the eighty-six portals (Figure 3) were obtained from tree different families combining friezes, shelfs, tympanums, etc. to parametrically generate the geometry needed and the use of profiles with different geometrical complexity allowed to obtain different LOG.
Moreover, all the families were predisposed for a high level of LOI, allowing to record information about the materials, such as the stone used, geological information, quarry of origin, structural and aesthetic properties and so on. In this regard, the actual texture and laying patterns of the flooring was captured through a photogrammetric process and used in the HBIM model.
Following this approach, after the definition of the portion of the ontology related to the vaults, the rules governing the geometry of the vaults were investigated. The systematic examination of vaults slowly appeared in Renaissance treatises starting from the work of Leon Battista Alberti in *De Re Aedificatoria*, who defined different vaults comparing them with their planimetric representation. Francesco Di Giorgio Martini in his Treatises on Architecture, Engineering and Military Art, briefly mentions the ancient vaults and describe as "modern" the sail vault and the lunettes vault. Lastly, Guarino Guarini, in *Del modo di disegnar le volte*, provided the comprehensive description on how to

construct lunettes vaults that was used in this work according to Spallone's work (Spallone, 2019).

Starting from the geometric principles and ancient methodologies passed on by the treatises, the adaptive families and the VPL scripts were implemented in Revit and Dynamo respectively. For both approaches a minimum number of parameters was chosen to generate the synthetic models in order to makes the cloud-to-bin procedure as simple and fast as possible while reducing the necessary operator inputs to the bare minimum. The vault dimensions in plan were defined directly conforming to the relative room and the only input data provided to the models from the survey were the spring plane height and a single rise for each vault measured in respect to the floor level. The number of lunettes for each side and the overhang of the curved surface were provided as extra input for the lunette vault and the mirror vault respectively. At this stage those data were manually collected from the point cloud. The vault typology was an implicit extra parameter used to choose the appropriate vault family.

The actual geometrical modelling of the vaults was carried out starting from the creation of a synthetic intrados surface through the generation of primitive geometries (i.e. planes and cylinders), Boolean intersections and loft operations. Lastly the vaults intrados surfaces were extruded to create solid models according to the historical documentation (Polichetti, 1985).

Adaptive families were implemented in Revit starting from the barrel vault. The four vertices of the quadrangular room covered by a barrel vault were used as adaptive points and as the basis of the modelling operation. For each head of the barrel vault, the profiles were created with an arch through three points using the aforementioned base vertices and a third point representing the crown of the arch and derived from the surveyed rise of the vault. The two arch profiles were then connected with a loft operation to create the intrados surface, then the obtained surface was subsequently extruded to generate the vault solid model.

Following the same approach, the pavilion and groin vaults were created generating two orthogonal barrel vaults, intersecting them, and selecting only the groins or the coves to obtain the base intrados surface for the extrusion.

The generation of the mirror vault intrados surface followed a slightly different procedure: the curved perimetral surface was generated extruding along the perimeter of the room a section line obtained as a circular arch through two points (i.e. the spring of the vault and the rise of the overhanging perimetral curved surface) and tangent both to the ceiling plane and the wall. This simplified construction was adopted with the aim of generalize the family and minimize the parameter needs for the generation of the geometry

Dynamo was used to implement the script to generate the more complex geometry of the lunettes vault and a flowchart representing it is reported in Figure 4, alongside part of the script related to the generation of the angular lunettes. The script takes as input the edges of the walls of the room, the relevant information about the vault positioning, such as the elevation of the floor and spring plane, and other geometrical feature like the number of lunettes and the rise of the vault. These inputs are then pre-processed to obtain all the data needed for the vault generation (Figure 4.a). Subsequently, a barrel vault is generated in the same way as described above (Figure 4.b), then, the two extremities of the barrel vault were cut with two prisms with a triangular base that has height equal to half the length of the short side of the barrel vault (Figure 4.c). The pavilion head vault is obtained lofting the diagonal edges resulted after the cutting operation on the battel vault (Figure 4.d); in that way the surface obtained connecting the two edges of the cut have the same

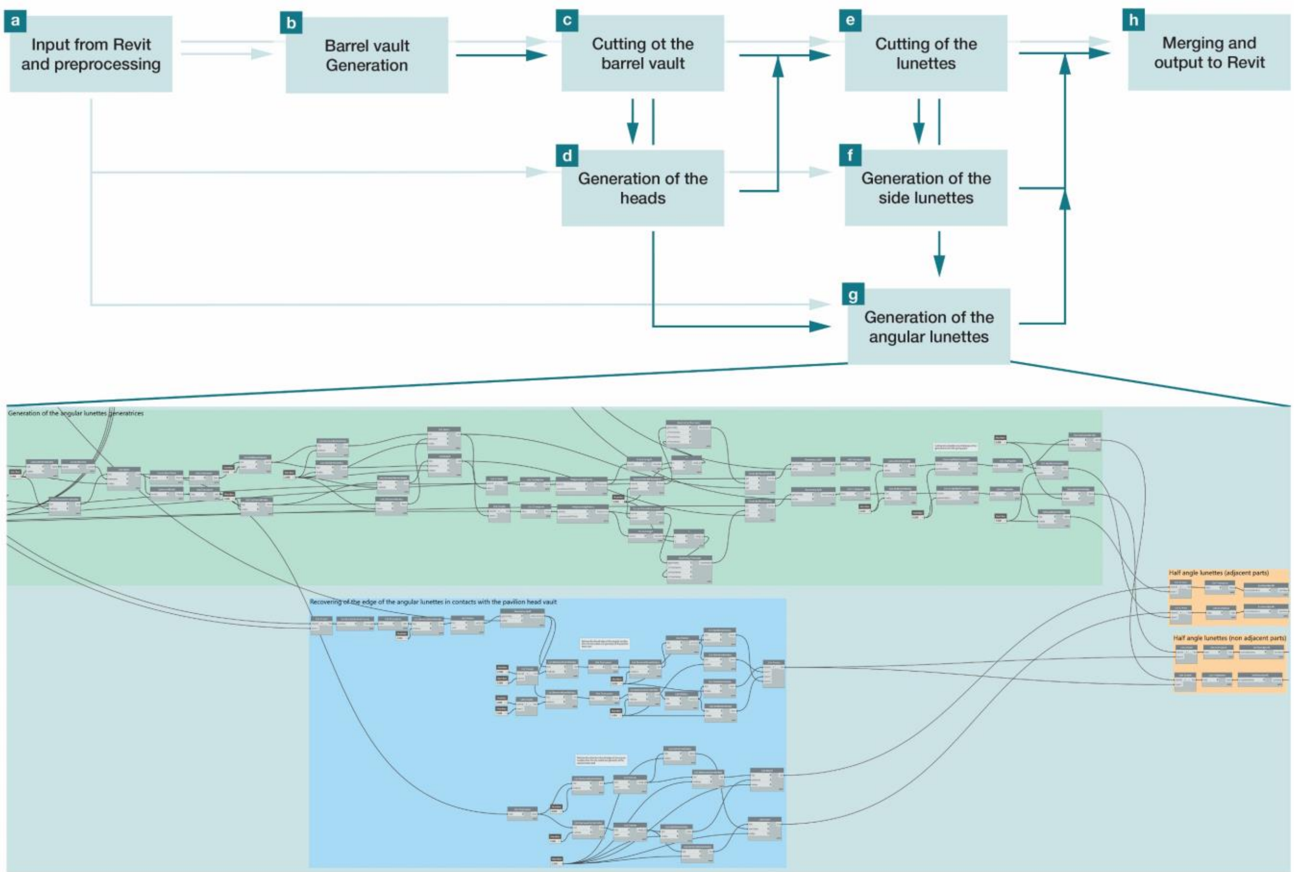

Figure 4: Flowchart of the Dynamo script implemented for the Lunette vault generation. Light harrow represents data transfer amongst blocks, darker ones represent geometry transfer. The portion of the Dynamo script dedicated to the generation of the angular lunettes is also reported.

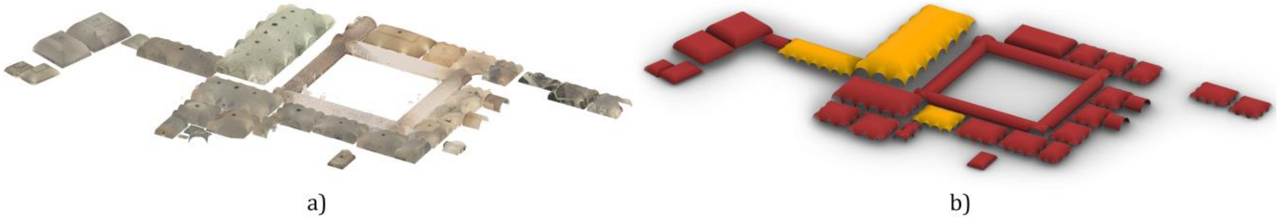

Figure 5: Vaulted ceilings of Urbino Ducal Palace main floor: a) point cloud survey; b) parametric model mesh. In orange are highlighted the three vaults taken into account in the deviation analysis.

curvature of the barrel vault itself, creating the desired pavilion head vault.

The lunettes were modelled with a similar technique following the work of Spallone on Guarini’s treatise (Spallone, 2019). On the base of the location of each lunette tip and the two springs of the generatrix arch, the geometries used to cut the base vault were generated. The geometry of the lunettes is obtained lofting the generatrix arches to the corresponding cut edges on the surface of the vault. The lunettes on the sides of the vault and the ones at the vertices are generated in Figure 4.f and Figure 4.g respectively.

All the lunettes were modelled of the same size and their position was calculates spacing them equally and so assuming corbels of the same size. This last assumption was not always compliant with the survey, but it was needed to generalize the vault description and it’s coherent with the aim to provide a synthetic representation of the architecture. As a last step all the geometries generated were collected in the complex geometry of the vault and (Figure 4.h) and then prepared to be imported in Revit as Direct Shapes.

An overview of the vault generated for the main floor of the Ducal Palace, alongside the surveyed point-cloud, is presented in Figure 5. In the image, the vaults that are present on the survey and are missing in the model are irregular vaults that cannot be generalized in families and therefore needed manual modelling: the figure demonstrates that the developed method allowed to cover almost all rooms.

5. RESULTS AND DISCUSSION

Thanks to the aforementioned procedures, it was possible to transfer the knowledge passed on by the ancient treatises, into the algorithms that defined the families identified during the definition of the ontology of the Ducal Palace. This process provided the tools needed to efficiently model the fifty-two vaults of the main floor with a good geometrical accuracy and an implicit coherence with planimetric distribution, due to the adaptive nature of the implemented families.

A quality assessment by the means of deviation analysis was performed on the BIM models of the pavilion head lunette vaults identified in orange in Figure 5 (i.e. the throne room, the *sala delle veglie* room and the *stanza della bossola* room) to prove the reliability of the VPL approach according to (Anil, Tang, Akinci, & Huber, 2013) and (Meyer, Brunn, & Stilla, 2023). The analysis was performed through the Cloud-to-Mesh Distance tool in CloudCompare (CloudCompare 2.12, 2021) computing the deviations between the surveyed point-cloud and the BIM model of the intradoses of the vaults. **Errore. L'origine riferimento non è stata trovata.** presents the results of the analyses in terms of absolute deviation showing some criticalities in the reconstruction. The two smallest vaults (i.e. b and c in figure) presents the maximum deviation in correspondence of the head of the lunettes and in correspondence of the sharp edges at the intersection between the main barrel and the heads of the pavilion. These two evidences can be respectively due to irregularities in the lunettes that are not taken into account in the VPL script and small deviation from the idealized model that are present in the constructed vault and can refer to constructive requirements.

The more significant inconsistencies are present in the throne room vault (Figure 6.a) and are mostly due to discrepancies between the idealized geometry used in the implementation of the pavilion head lunette vault family and the actual geometry of the vault.

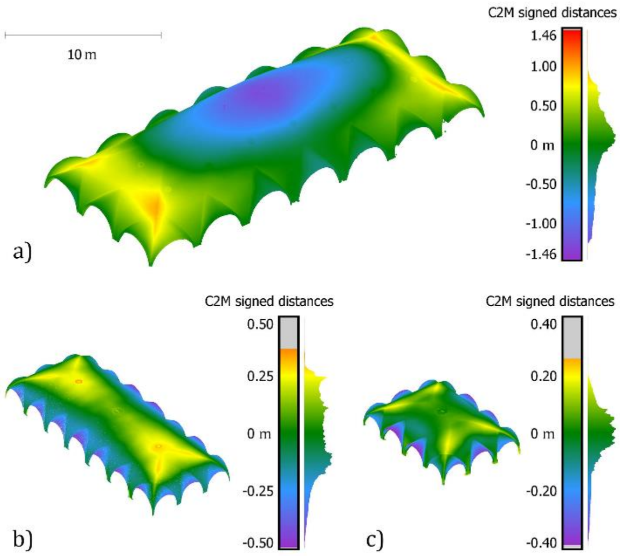

Figure 6: Cloud to mesh distance computed between the surveyed and the reconstructed geometries. A) throne room; b) *sala delle veglie*; c) *stanza della bossola*. All distances are in meters.

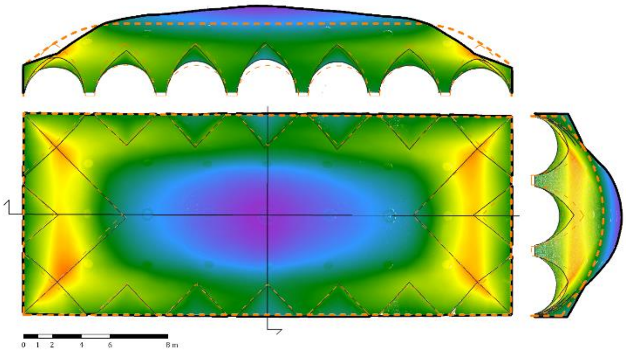

Figure 7: Comparison between the surveyed (in black) and the reconstructed geometry (in orange) in plan and sections superimposed to the deviation analysis. The most significant

discrepancies are in the centre of the vault, where the actual geometry differ from the Guarini's idealized lunette vault implemented in the VPL.

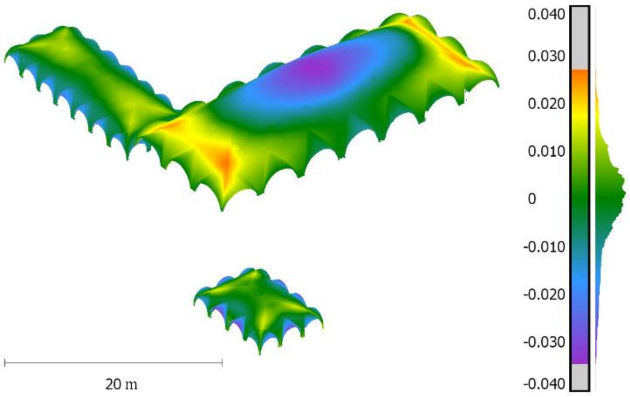

Figure 8: Cloud to mesh dimensionless distance. For each vault, the distances computed were adimensionalized by the length of the diagonal of the same vault. This allow for a comparison amongst the different vaults and shows how the smallest vaults, which more accurately follow the Guarini's model, present discrepancies to the survey that are less than 2% of the length of the diagonal.

During this work it was noted how the throne room vault, despite its overall double symmetry, it's far from being regular, presenting double curvature surfaces and significant changes in curvature between its lower and highest part.
To highlight these findings a superimposition between the plan projections and the sections of the two geometries of the throne room and the deviation analysis is presented in Figure 7. From this analysis is clear how the pavilion head lunette vault family is not completely suitable for this case and another family or local modelling should be used if better accuracy is needed.
To compare the reconstruction accuracy among different vaults and to provide a relative measurement of deviation, the Cloud-to-Mesh distance computed before was adimensionalized with the length of the diagonal of each vault and the resulting deviation maps are shown in Figure 8. On one hand, this analysis confirms the findings already discussed regarding the accuracy of the reconstruction of the single vaults but, on the other hand, it shows that beside the absolute discrepancies appear significant and highly variable in the different vaults, when showed as relative discrepancies demonstrate how the deviations are actually limited if compared with the size of the structure and the vaults themselves, and the values of deviation obtained are comparable among the three vaults analysed.
A summary of the results of the analyses is reported in Table 1: the length of the diagonal of each vault, used in the adimensionalization is reported alongside the maximum deviation measured. The standard deviation of the distribution of lengths measured in the deviation analysis was also reported. From those data can be seen how, despite the incorrect model used for the throne room reconstruction, the overall deviation is below the 3% of the vault diagonal, and half this value in the case of the other two vaults where the model implemented in the VPL script better fits the actual geometry of the ceiling.

Vault	Vault diagonal (m)	Max deviation (m)	2 σ (m)	Adim. 2σ
Throne room	36.35	-1.27	0.97	0.027
Sala delle veglie	21.59	-0.50	0.32	0.015
Stanza della bossola	12.97	-0.39	0.21	0.016

Table 1. Summary of the deviation analysis conducted in the three sample vaults.

Those analyses show that overall, the modelling errors are small for architectural elements of this size and this complexity. The result was a synthetic representation of the ceiling with a lower level of detail but compatible with the other elements of the HBIM model, which allowed both to enrich it with the available information about the vaults and to obtain a high visual quality in the rendered outputs, also allowing to exploit the model for enjoyment applications (Figure 9) from (Ferretti, Quattrini, & D'Alessio, 2022).

6. CONCLUSIONS AND FUTURE WORK

The aim of this work was to automatize the generation of synthetic vaults in BIM environment, creating a library of suitable families for the representation of the vaults of Urbino Ducal Palace and similar Italian renaissance architecture. In this

Figure 9: Rendering of the Throne Room of the Ducal Palace with the most complex lunette vault of the main floor.

regard, the definition of adaptive families in Revit appeared to be the easiest and most efficient solution able to capture the relationships amongst the objects and to fulfil the needs of parametrization, although it is suitable only for vaults of moderate geometrical complexity. The VPL approach on Dynamo, despite being more flexible and able to generate complex geometries, it's unable to conserve the information relative to the relationship among different elements of the model, requiring, as an example, a new generation of the vault geometry in case of a modification to the walls of the room.
The use of parametric modelling for vaults in cultural heritage proved to be efficient and reliable: it was able to partially automate and significantly reduce work time in the HBIM implementation of a huge complex like the Ducal Palace and was able to provide models of suitable accuracy, while also taking into account the size and the complexity of those geometries. The weakness of these approaches is that their implementation requires a significant computational effort and for this reason the use of local models is still the best option for the generation of unique geometries when it's not possible to take advantage of the standardization nor the repetition of the parametric approach. A further development of the research could be the automatic extraction of the geometrical features of the vaults to be used as input parameters in the family implementation. This step could reduce the need for the complex and time-consuming operations of measurement on the point cloud which usually rely on the judgment of the operator and lead to errors. The increased number of parameters automatically obtained in this way could make sustainable to provide more input data for the geometrical description in family implementation allowing for more complex programming able to provide more accurate geometry reconstruction.

ACKNOWLEDGEMENTS

The survey activities were authorised by MIC, Ministry of Culture - General Directorate for Museums - National Gallery of Marche. The authors thank also Prof. Paolo Clini as Principal Investigator of the CIVITAS project. and Luigi Sagone and Floriano Capponi for the survey campaign. The authors acknowledge that a significant part of this work is part of the Master's Degree Thesis in Building Engineering–Architecture by Giorgia de Angelis and Umberto Ferretti.

BIBLIOGRAPHY

Angjeliu, G., Cardani, G., & Coronelli, D. (2019, 09). A parametric model for ribbed masonry vaults. *Automation in Construction, 105*. doi:10.1016/j.autcon.2019.03.006

Anil, E., Tang, P., Akinci, B., & Huber, D. (2013). Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data. *Automation in Construction*, 507-516. doi:10.1016/j.autcon.2013.06.003

Apollonio, F., Gaiani, M., & Sun, Z. (2017). A reality integrated BIM for architectural heritage conservation. In *Handbook of research on emerging technologies for architectural and archaeological heritage* (p. 31-65). IGI Global.

Argiolas, R., Cazzani, A., Reccia, E., & Bagnolo, V. (2019, 08 20). From LIDAR data towards HBIM for structural evaluation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 125-132. doi:10.5194/isprs-archives-XLII-2-W15-125-2019

Attico, D., Turrina, A., Banfi, F., Grimoldi, A., Landi, A. G., Condoleo, P., & & Brumana, R. (2019). The HBIM analysis of the geometry to understand the constructive technique: the use of the trompe volume in a brick vault. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. doi:10.5194/isprs-archives-XLII-2-W11-107-2019

Aubin, P. (2013). *Renaissance Revit: Creating Classical Architecture with Modern Software.* Scotts Valley, CA, USA: CreateSpace Independent Publishing Platform.

Bagnolo, V., & Argiolas, R. (2021). Scan-to-BIM Process Versus 3D Procedural Modelling of Gothic Masonry Vaults. In *From Building Information Modelling to Mixed Reality* (p. 17-31). Cham: Springer International Publishing.

Banfi, F. (2019). HBIM generation: extending geometric primitives and BIM modelling tools for heritage structures and complex vaulted systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 139–148. doi:10.5194/isprs-archives-XLII-2-W15-139-2019

Bardi, B. (1706). *Encomio della patria di monsignor Bernardino Baldi da Urbino abate di Guastalla.* per Angelo Ant. Monticelli.

Brumana, R., Condoleo, P., Grimoldi, A., & Landi, A. (2017, 5 15). Shape and construction of brick vaults. Criteria, methods and tools for a possible catalogue. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 137-143.

Brumana, R., Della Torre, S., Previtali, M., Barazzetti, L., Cantini, L., Oreni, D., & Banfi, F. (2018, 12). Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention. The Basilica di Collemaggio (L'Aquila). *Applied Geomatics, 10*(4), 545-567. doi:https://doi.org/10.1007/s12518-018-0233-3

Brumana, R., Stanga, C., & Banfi, F. (2022). Models and scales for quality control: Toward the definition of specifications (GOA-LOG) for the generation and re-use of HBIM object libraries in a Common Data Environment. *Applied geomatics, 14*, 151–179. doi:https://doi.org/10.1007/s12518-020-00351-2

Capone, M., & Lanzara, E. (2019). Scan-to-BIM vs 3D ideal models HBIM: Parametric tools to study domes geometry. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 219-226. doi:https://doi.org/10.5194/isprs-archives-XLII-2-W9-219-2019

Clini, P., Quattrini, R., Bonvini, P., Nespeca, R., Angeloni, R., Mammoli, R., . . . Leopardi, A. (2020). Digit (al) isation in Museums: Civitas Project–AR, VR, Multisensorial and Multiuser Experiences at the Urbino's Ducal Palace. *IGI Globa*, 194-228.

Croce, V., Caroti, G., De Luca, L., Jacquot, K., Piemonte, A., & Véron, P. (2021). From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. *Remote Sensing*, 461. doi:https://doi.org/10.3390/rs13030461

Ferretti, U., Quattrini, R., & D'Alessio, M. (2022). A Comprehensive HBIM to XR Framework for Museum Management and User Experience in Ducal Palace at Urbino. *Heritage*, *5*(3), 1551-1571. doi:https://doi.org/10.3390/heritage5030081

Fiorillo, F., Rossi, C., & Morandi, M. (2021). Two methodologies for the virtual reconstruction of the architectural remains of a Late Roman archaeological site based on the 3D point cloud. *DISEGNARECON*. doi:https://doi.org/10.20365/DISEGNARECON.27.2021.6

GPL software. (2021). CloudCompare 2.12. Tratto da http://www.cloudcompare.org/

Grilli, E., & Remondino, F. (2019). Classification of 3D Digital Heritage. *Remote Sensing*. doi:https://doi.org/10.3390/rs11070847

Jing, Y., Sheil, B., & Acikgoz, S. (2022). Segmentation of large-scale masonry arch bridge point clouds with a synthetic simulator and the BridgeNet neural network. *Automation in Construction, 142*. doi:https://doi.org/10.1016/j.autcon.2022.104459

López, F., Lerones, P., Llamas, J., Gómez-García-Bermejo, J., & Zalama, E. (2018, 5 5). A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technologies and Interaction, 2*(2), 21. doi:https://doi.org/10.3390/mti2020021

Marissia, D., Maria I, M., Melinos, A., Andreas C, A., Pratheba, S., Evangelos, K., . . . George, A. (2021). A 3D digitisation workflow for architecture-specific annotation of built heritage. *Journal of Archaeological Science: Reports*. doi:https://doi.org/10.1016/j.jasrep.2020.102787

Meyer, T., Brunn, A., & Stilla, U. (2023). Geometric BIM verification of indoor construction sites by photogrammetric point clouds and evidence theory. *ISPRS Journal of Photogrammetry and Remote Sensing*, 432-445. doi:https://doi.org/10.1016/j.isprsjprs.2022.12.014

Morbidoni, C., Perdicca, R., Paolanti, M., Quattrini, R., & Mammoli, R. (2020, 12). Learning from Synthetic Point Cloud Data for Historical Buildings Semantic Segmentation. *Journal on Computing and Cultural Heritage, 13*(4), 1-16. doi:https://doi.org/10.1145/3409262

Moreira, A., Quattrini, R., Maggiolo, G., & Mammoli, R. (2018, 5 30). HBIM methodology as a bridge between Italy and Argentina. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 42*(2), 715-719. doi:https://doi.org/10.5194/isprs-archives-XLII-2-715-2018

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey, 27*(4), 311-327. doi:https://doi.org/10.1108/02630800910985108

Pierdicca, R., Paolanti, M., Matrone, F., Martini, M., Morbidoni, C., Malinverni, E., . . . Lingua, A. (2020). Point cloud semantic segmentation using a deep learning framework for cultural heritage. *Remote Sensing*. doi:https://doi.org/10.3390/rs12061005

Polichetti, M. (1985). *Il Palazzo di Federico da Montefeltro: restauri e ricerche.* Urbino: Quattroventi.

Spallone, R. (2019). Lunette Vaults in Guarini’s Works. Digital Models between Architettura Civile and Modo di misurare le fabriche. *Diségno*(4), 91-102. doi:10.26375/disegno.4.2019.10

Spallone, R., & Calvano, M. (2022, 6). Parametric Experiments on Palladio’s 5 by 3 Villas. *Nexus Netw J, 24*, 287–313. doi:10.1007/s00004-022-00592-1

Stiny, G., & Mitchell, W. (1978). The Palladian Grammar. *Environment and Planning B: Urban Analytics and City Science, 5*(1). doi:https://doi.org/10.1068/b050005

Teruggi, S., Grilli, E., Russo, M., Fassi, F., & Remondino, F. (2020). A hierarchical machine learning approach for multi-level and multi-resolution 3D point cloud classification. *Remote Sensing*. doi:https://doi.org/10.3390/rs12162598

Volk, R., Stengel, J., & Schultmann, F. (2014, 3). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction, 38*, 109-127. doi:10.1016/j.autcon.2013.10.023

Zhai, R., Zou, J., He, Y., & Meng, L. (2022). BIM-driven data ugmentation method for semantic segmentation in superpoint-based deep learning network. *Automation in Construction*. doi:https://doi.org/10.1016/j.autcon.2022.104373.