From Integrated Survey to Semantically-Enriched Models: An H-BIM Pipeline for Developing Descriptive Systems to Understand Architectural Heritage

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Abstract

The paper presents an operational methodology based on the interaction between digital survey, point cloud segmentation, formal encoding, and parametric modelling, applied to three fortified portals associated with the work of Michele Sanmicheli and his cultural legacy. From photogrammetric and laser scanning surveys, the point clouds were subjected to macro- and micro-segmentation processes, to encode architectural types according to compositional and hierarchical logics.
The subsequent parametric modelling is grounded in the abstraction of profiles and the construction of nested families within a BIM environment, encoded and structured according to the principles of Sanmichelian architecture. Through a systematic comparison between ideal models and surveyed reality, it was possible to adapt geometries to the specificities of the built elements, while preserving their original proportional rules.
Integrating topologically complex meshes through visual programming techniques enabled the accurate representation of decorative features. The results highlight the potential of this operational methodology in constructing flexible, proportionally coherent information systems aligned with the architectural lexicon, offering new tools for documenting and enhancing fortified heritage.

1. Introduction

The structuring of semantically-enriched information models, understood as digital frameworks in which geometry is associated with formal typologies, hierarchical relations, and qualitative information, when applied to cultural heritage, proves to be an effective tool for a deeper understanding of the geometric, spatial, compositional, and technological aspects of complex architectural systems. In this regard, using digital survey systems to support the implementation of three-dimensional models enables the acquisition and representation of the complexities of architectural heritage in a detailed and accurate manner. While these technologies are now capable of meeting the requirements of precision and morphometric completeness, they still remain distant from the cognitive dimensions of architectural representation. This raises a series of heterogeneous issues, relating not only to the relationship between the architectural element and the building as a whole, but also to the definition of hierarchical and spatial systems for encoding the relationships among the elements.
These theoretical aspects are closely linked to practical issues concerning the management and processing of digital data for the development of geometric representations, as well as the methods for structuring and connecting information. In this sense, morphometric complexity represents only one component of the communicative element, which must also incorporate abstract realities and qualitative interpretations. From a comprehensive perspective, these contribute to the construction of a system of fixed and interconnected three-dimensional relationships among meaningful “objects” (Parrinello & Pettineo, 2025).
This leads to several questions regarding the degree of approximation of the geometric component, the actual need for its correspondence with reality, and what types of information, and of what nature, can be meaningfully associated with it. Based on these considerations, an operational workflow is presented for structuring semantically-enriched information models, starting from processing raw data acquired through digital surveying. Through the integration of different processing systems and the subsequent segmentation of point clouds, the results are illustrated concerning three architecturally related systems linked to the work of Michele Sanmicheli and his cultural legacy: the Portal of the *Sant’Andrea* fortress in Venice (Italy), *Porta di Terraferma in Zadar*, and the Portal of *San Nicolò* fortress in Šibenik, (Croatia).
In the case of Sanmichelian architecture − characterised by a refined articulation of the architectural language adapted to fortification − the use of information models enables an examination of the internal coherence of design choices and the local variations of recurring typological and decorative solutions. The structures selected for this study offer a privileged context to test segmentation and parametrisation methodologies, precisely due to their stylistic homogeneity and geometric complexity. Within this framework, the interaction between digital surveying, parametric modelling, and information structuring forms the core around which the proposed workflow is articulated.

2. Related works

The use of semantically-enriched information models today represents one of the most promising tools for overcoming the dichotomy between geometric reproduction and the cognitive representation of historical architecture. By this term, we refer to a model in which geometry is enriched with formal, functional, and documentary information, and structured according to typological and hierarchical logics coherent with architecture's language (De Luca, 2011). Within architectural heritage, associating digital objects with meanings, functions, and formal relationships enables a transition from a purely descriptive approach to an effective multilayered information system, capable of supporting historical, morphological, and constructive analyses. This vision is consistent with certain theoretical developments in the literature, which underline the necessity of integrating semantic descriptions and geometric models through informational structures that reflect the lexicon and grammar of architecture (Apollonio et al., 2012; Costamagna & Spanò, 2012; De Luca et al., 2014; Attenni, 2019).
For this purpose, it is essential to consider digital surveying not as an end but as a starting point for the construction of stratified knowledge, grounded in the relationship between form, function, and meaning. The adoption of HBIM systems for historic architecture requires the development of parametric libraries capable of representing not only objects' morphology but also

their formal evolution, construction techniques, and the transformations they have undergone over time (Murphy & Dore, 2012).

Surveying thus becomes a process of reverse engineering, which, through semantic segmentation and profile abstraction, allows for the reconstruction of the formal and compositional intentionality of the original makers. In recent years, particular attention has been devoted to structuring digital *abaci* and three-dimensional glossaries − fundamental tools for formalising architectural knowledge within HBIM environments (Parrinello & Dell'Amico, 2021).

The implementation of digital libraries structured according to hierarchical and semantic logics enables the construction of accurate models consistent with the language of historic architecture (De Luca et al., 2007; Remondino et al., 2012; Quattrini et al., 2017). These repositories act as interpretative interfaces between geometric data and its semantic dimension, facilitating complex architectural elements' typological recognition and reproduction (Croce et al., 2021).

Moreover, implementing specific databases and information structures allows the systematic organisation of digital objects and the encoding of spatial, functional, and compositional relationships among them (Oreni et al., 2014). These tools represent key components for promoting interoperability, data traceability, and terminological consistency within complex HBIM models. The definition of shared architectural nomenclatures and digital glossaries has proven essential to ensure terminological coherence and support digital models' semantic enrichment, through the adoption of open and interoperable ontological structures (Maietti et al., 2017; Sanseverino, 2024). These instruments constitute central components for fostering traceability, informational sustainability, and interdisciplinary collaboration in heritage documentation and conservation processes.

3. Developed Methodology

Building on established practices in integrated digital surveying, an operational methodology has been defined for structuring a digital database as a preparatory foundation for implementing information models enriched with semantic attributes. These attributes support the study and understanding of the proportional and compositional characteristics and relationships found in Sanmicheli's works. The entire methodological process has been tested on three emblematic case studies, selected for their typological similarities and shared cultural matrix: the Portal of *Sant'Andrea* fortress in Venice, *Porta di Terraferma* in Zadar, and the Portal of *San Nicolò* fortress in Šibenik.

While the first two works are generally attributed to Michele Sanmicheli, the attribution of the Portal of *San Nicolò* fortress remains a subject of scholarly debate. Recent studies tend to ascribe the work to Giangirolamo Sanmicheli, nephew of the Veronese architect, who was active in the Adriatic region in the second half of the sixteenth century and continued his uncle's architectural language (Žmegač, 2005). The workflow was applied to these three contexts to assess its effectiveness in the analysis and modelling of complex architectures within fortified heritage. It was structured around four primary levels, or operational phases: *acquisition, interpretation, formalisation*, and *characterisation*.

3.1 Acquisition and structuring of digital survey data

The three case studies were documented using close-range photogrammetric survey techniques (both terrestrial and UAV-based), integrated with terrestrial laser scanning (TLS) instrumentation (Parrinello & La Placa, 2020; Galeazzo & Parrinello, 2024). The data processing phase involved the comparison of different software and data treatment methodologies, with varying levels of integration of TLS point clouds into the photogrammetric processing workflow. The point cloud database was structured by evaluating the most appropriate strategy for ensuring the readability of complexity and specific features, particularly decorative elements and ornaments. This required consideration of several technical factors, such as the nature and format of the generated files, software interoperability requirements, and the management of dataset sizes, which in some cases exceeded several tens of gigabytes.

An initial phase involved the alignment of laser scans using Leica Cyclone, followed by data export in .e57 format. The resulting databases included the complete architectural complexes corresponding to the three case studies, encompassing the fortified structures within which the portals are located.

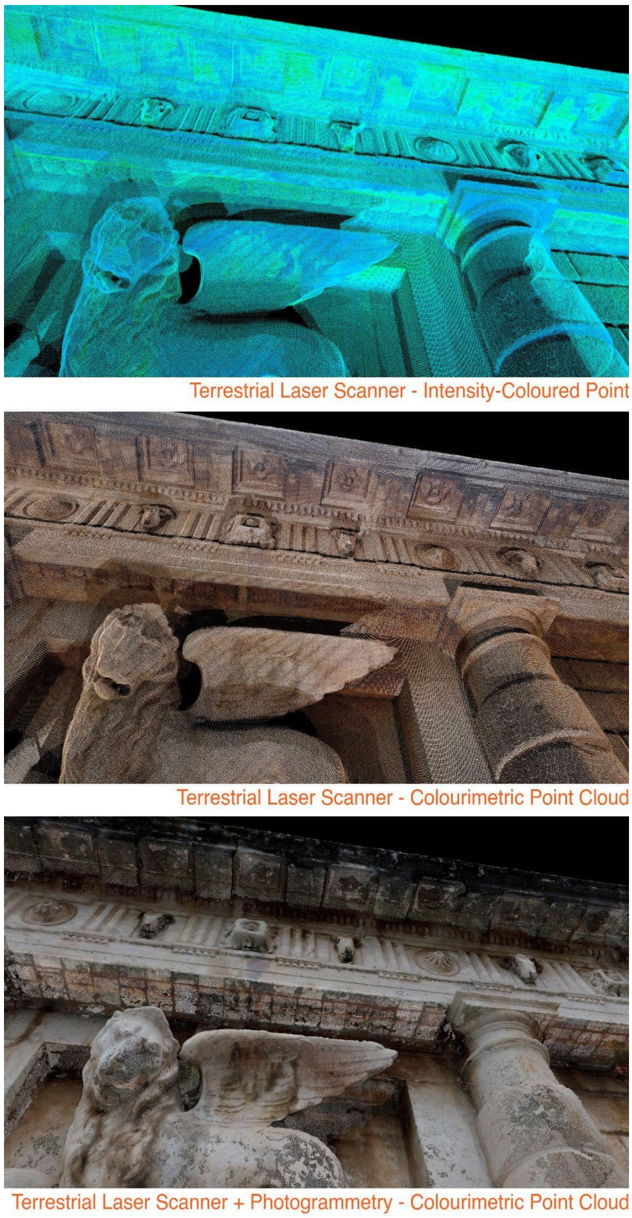


Figure 1. Assessment of Digital Survey Data Quality – *Porta di Terraferma*, Zadar.

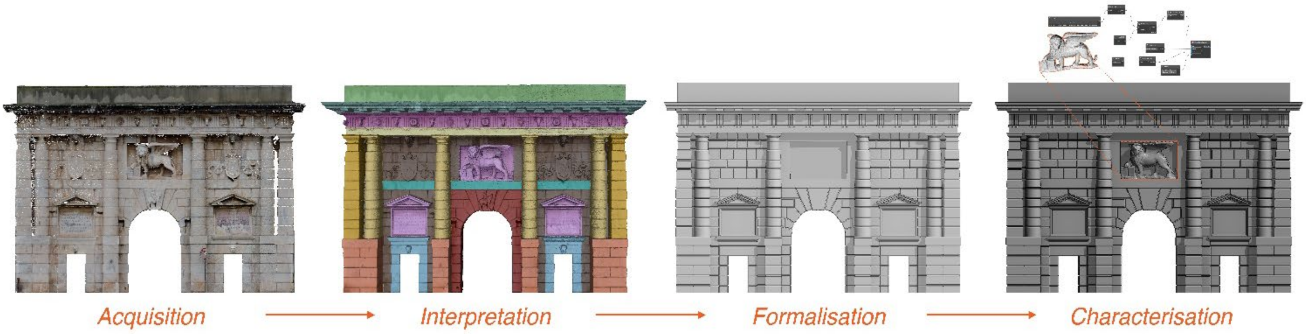


Figure 2. The methodological workflow for structuring H-BIM models comprises the acquisition of digital data through integrated photogrammetric and laser scanning surveys, the semantic segmentation of point clouds to support the interpretation of architectural elements and their formalisation through parametric modelling based on abstracted profiles and hierarchical rules, and the final characterisation of the model by aligning ideal geometries with the surveyed state and incorporating ornamental meshes via visual programming languages.

In a subsequent phase, the data corresponding to the portal areas was isolated (macro-segmentation), as these were selected as the focus for detailed information modelling.
The filtered datasets were then imported into RealityCapture, which was chosen as the main photogrammetric processing software over alternatives such as Agisoft Metashape, due to its more efficient handling of complex geometries and optimised workflows, particularly in terms of processing time (Pettineo et al., 2024).
From the geometric base structured via TLS, photographic datasets relating to the portals, extracted from the complete surveys of the fortresses, were imported. The resulting data was then filtered in CloudCompare using spatial subsampling techniques to reduce noise, optimise density, and facilitate accurate interpretation of the geometries.

3.2 Interpretation and Segmentation of Raw Geometric Data

The structured databases related to the three case studies were subjected to a segmentation process based on technological and formal aspects, derived from a compositional analysis of the portals. This approach facilitated data management and enabled an initial spatial understanding of the structures. Segmentation played a crucial role in separating and encoding different types of architectural elements, while supporting the subsequent management and import of point clouds into the BIM authoring software Autodesk Revit, used for defining the geometric model. Point cloud processing was carried out manually within Autodesk Recap Pro, to achieve a controlled stylistic and semantic decomposition, based on the recognition and classification of elements according to the constituent parts of the architectural order (micro-segmentation). This methodological choice proved preferable to automated segmentation techniques based on parameters such as curvature, density, or surface orientation, which in this context risked introducing arbitrary distinctions between architectural components (Murtiyoso & Grussenmeyer, 2019). For each case study, the segmented cloud was divided into regions and imported into Revit to initiate the process of geometric and formal parametrisation.
This process involves a functional and typological classification, based on the recognisability of the elements and their coherence with a codified formal repertoire. Using shape grammar principles and classical architectural languages provides an essential reference for organising objects according to hierarchical, spatial, and constructional relationships.

3.3 Parametric Formalisation and Model Structuring

The parametrisation of architectural elements followed a methodology based on analysing geometric profiles, typological codification, and identifying compositional rules. During this phase, an in-depth study of Sanmicheli's work was carried out, integrating historical sources and architectural treatises with the data obtained from the digital survey. Particular reference was made to *Li cinque ordini dell'Architettura Civile* (Sanmicheli, 1735), with specific attention to the proportional relationships

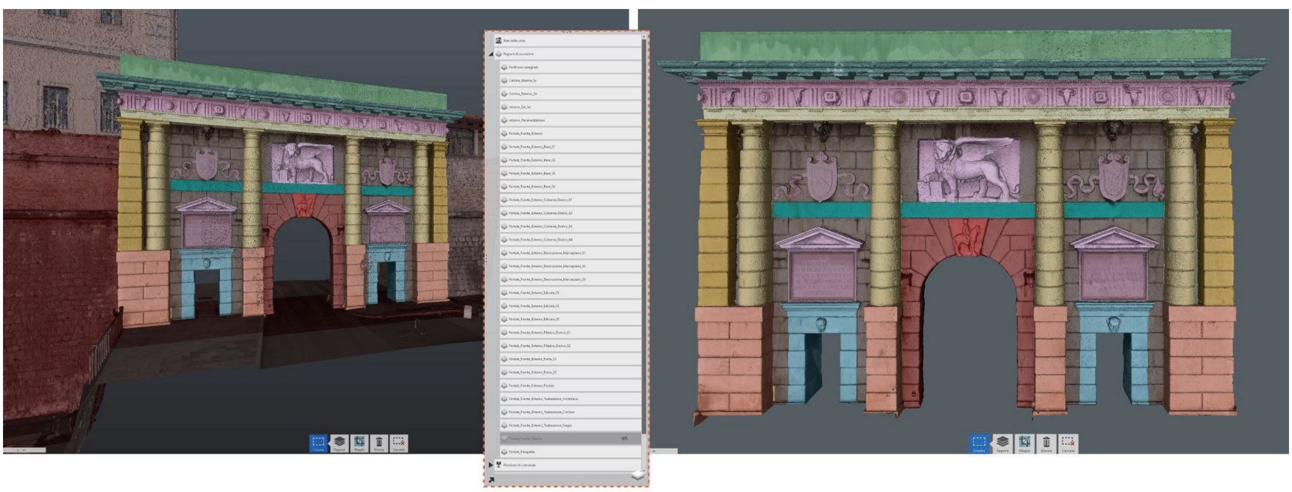


Figure 3. *Interpretation.* Semantic micro-segmentation process within Autodesk Recap Pro, Porta di Terraferma, Zadar.

and architectural orders described therein, as well as to later nineteenth-century publications such as *Le fabbriche civili, ecclesiastiche e militari di Michele Sanmicheli* (Ronzani et al., 1862), in which the portals examined in this study are documented through descriptions, graphic surveys, accurate measurements, and proportional diagrams.

The analysis of these materials enabled the construction of idealised versions of architectural elements, structured according to classical modules, Sanmicheli's reinterpretations, and recognisable formal logics. The development of these digital *abaci* followed a modular and compositional logic, allowing for a coherent transposition between architectural theory and HBIM-based parametric modelling. The definition of profiles was not limited to a mere geometric transposition. Instead, it constituted the first level of abstraction in creating a parametric *abacus* consistent with architectural composition rules. Comparative analysis of the three portals revealed significant morphological and stylistic variations, which could be traced back to a shared design framework. This coherence made it possible to define a common formal matrix suitable for generating adaptable parametric elements, capable of expressing the specific features of each case study and the unity of the overall corpus.

The construction of these ideal elements focused particularly on the architectural orders employed in the portals under examination. While acknowledging the design specificities of each work, the modelling followed a unified logic aimed at representing the recurring formal, structural and decorative features of Sanmicheli's architectural language. In all three cases, a set of generative objects was defined and organised into nested families, based on formal rules consistent with the original works and designed to support the development of informative parametric models. For the architectural orders in particular, individual components (such as base, shaft and capital for columns, and architrave, frieze and cornice for entablatures) were modelled through the definition of parametric profiles and subsequently integrated into their respective families.

During the parametrisation of the geometric and compositional elements of the portals, a nested structure was defined within the system families. This approach, as exemplified by the case of the engaged columns, allowed for the articulation of complex components through parametric dimensional relationships across different levels of the family, thereby accurately reflecting the compositional logic of the portals. Within the column families, elements such as the capital and the individual drums of the shaft were distinguished and organised via nesting, contributing to the definition of the overall geometric and compositional unit.

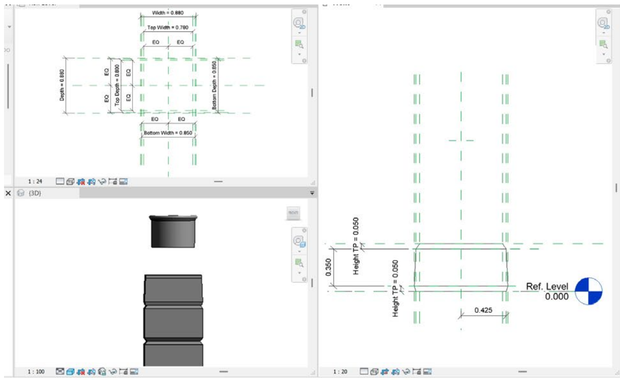
The creation of nested families within the BIM environment proved essential for modelling articulated objects, as it allowed for precise control over parameters and proportions across the entire system. However, such complexity demands rigorous management, based on rules that ensure stylistic coherence and consistency. Nesting, understood as including one or more families within another, represents one of the fundamental principles in implementing complex families, tailored to the specific requirements of informative modelling applied to historical heritage forms.

A theoretical investigation into Sanmicheli's use of architectural orders provided deeper insight into the design choices underpinning the construction of digital *abaci* and the parametric modelling of the portals. Sanmicheli does not merely apply Vitruvian principles in an academic manner; rather, he develops an original architectural language in which the order is never reduced to mere decoration, but assumes a structural and tectonic value (Pagliara, 1994; Davies & Hemsoll, 2004).

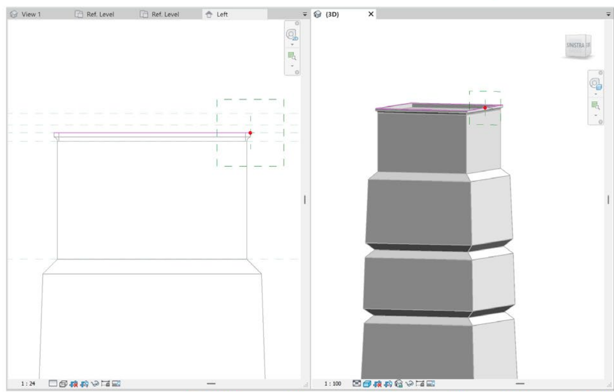
This inherently structural conception is mirrored in the HBIM modelling process, where hierarchical relationships between components and proportional constraints were defined to reflect such interdependence.

Sanmicheli's reinterpretation of the Doric order − widely employed in the analysed portals − demonstrates a distinctive synthesis of archaeology and design, in which classical sources are critically appropriated and reworked in response to context. The Veronese architect thus develops a lexicon in which, despite drawing from ancient models, the order is not a fixed formal module but a flexible system capable of reflecting functional, symbolic, and material requirements.

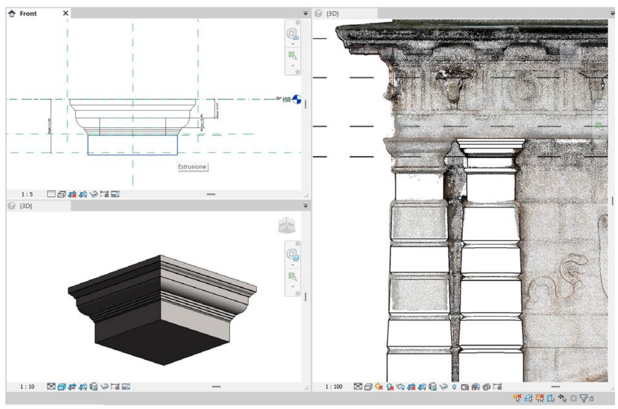
The HBIM modelling process thus engaged with a complex architectural lexicon that blends classical principles with a strong experimental attitude. The components of the orders were conceived to accommodate typological and stylistic variations, with particular attention to decorative detail. Where necessary − as in the case of the entablature − the various profiles were designed in mutual relation, enabling coordinated manipulation consistent with the original proportional logic.



Parametrization of column drums and profile control



Definition of the moulding profiles of the capitals



Organization of nested families

Figure 4. *Formalisation*. Selected stages in the definition of parametric elements.

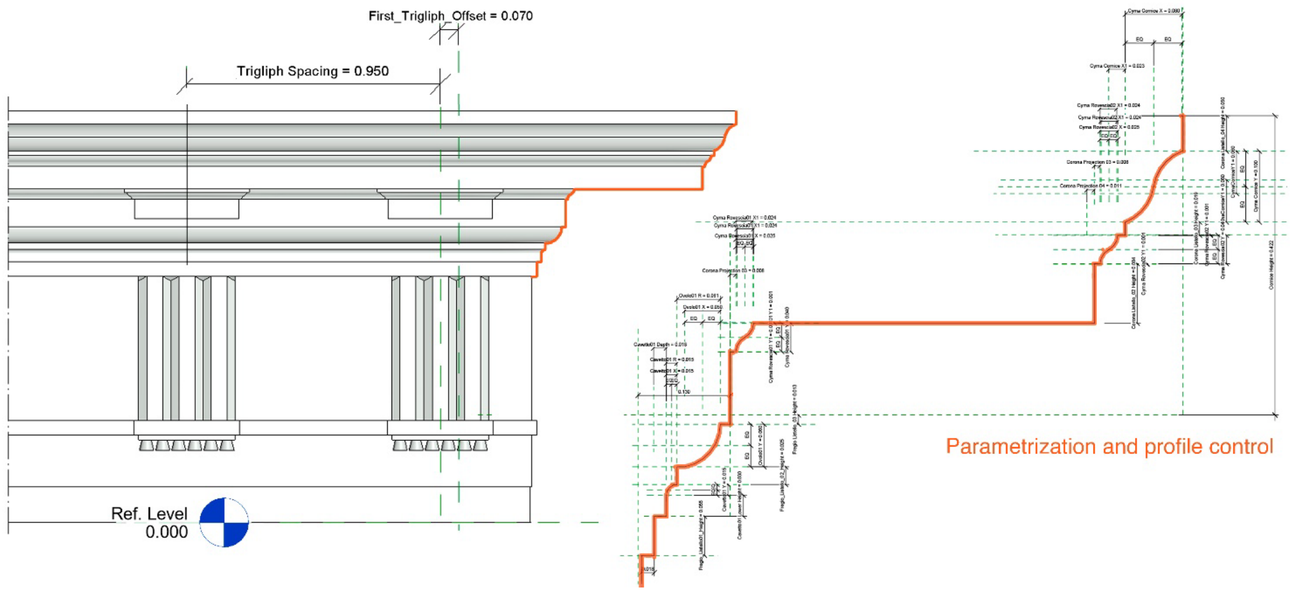


Figure 5. *Formalisation.* Parametric structure of the architrave from the *Porta di Terraferma* portal in Zadar.

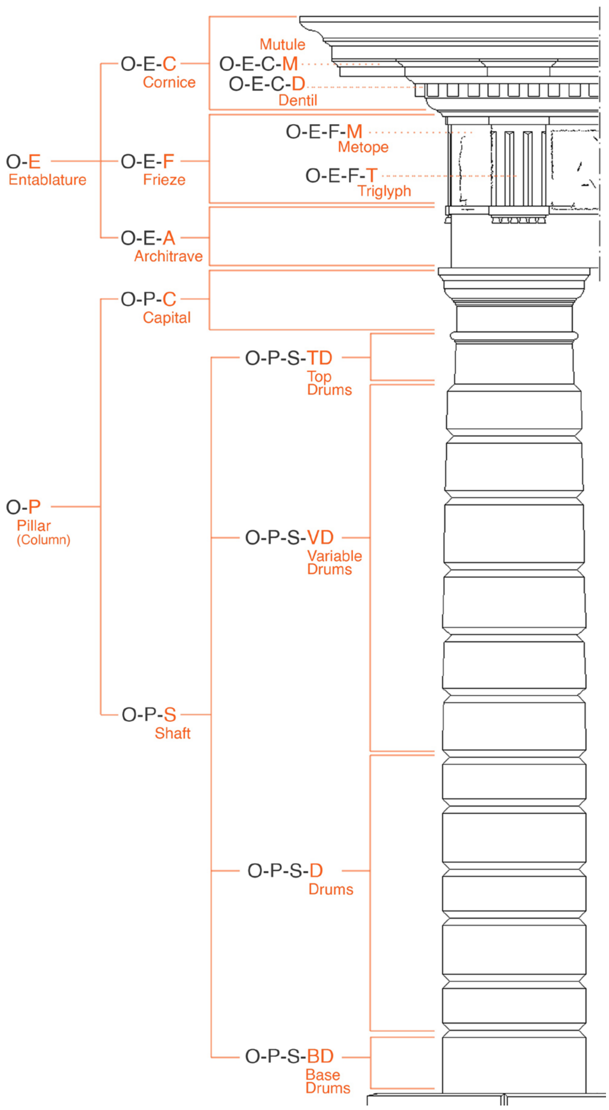


Figure 6. *Formalisation*. Hierarchical Structure and Codification of Nested Families reflecting components in Sanmicheli’s interpretation of Architectural Order, Gate of *St. Andrea Fortress*.

A particularly significant aspect was the control of the column shaft’s deformation, achieved through the parametric manipulation of individual drums.
This allowed for the modelling of a curvilinear profile which, while recalling the classical tradition of *entasis*, departs from it to assume a more marked and expressive character, in line with the Sanmicheli’s reinterpretation of the architectural lexicon. At the same time, consistency with the modular articulation of the element was preserved.

3.4 Characterisation of the models

Once the architectural elements had been modelled in their “ideal” form, they were adapted to the three-dimensional model through direct comparison with the imported point cloud to achieve an accurate correspondence with the surveyed reality of the architectural features. During the modelling of the existing condition, adding additional deformation parameters made it possible to adjust the ideal geometries derived from the theoretical model to the irregularities and specificities observed in the point cloud analysis, enabling a calibrated alignment between ideal and actual conditions. The resulting geometries were further refined to fit measured surfaces through dimensional constraints and automatic adaptation rules, with particular attention paid to the correspondence between theoretical modules and surveyed deformations.
This process allowed for integrating design theory with physical reality, ensuring that the parametric model corresponded closely to the as-found condition. The characterisation phase also marked a critical step in integrating ornamental and sculptural features into the information model, which are not easily managed through conventional parametric families. For ornamental and statuary elements, high-resolution meshes were imported as instances using visual programming techniques (VPL).
The workflow optimised the management of complex geometries and facilitated the accurate integration of decorative and sculptural elements into the parametric model. Based on the point cloud data acquired through laser scanning and photogrammetry, high-density polygonal meshes were generated using MeshLab and optimised to ensure morphological accuracy. These meshes were then imported as instances and associated with the HBIM model via visual scripts developed in Dynamo, which enabled their correct positioning and orientation. This VPL-based

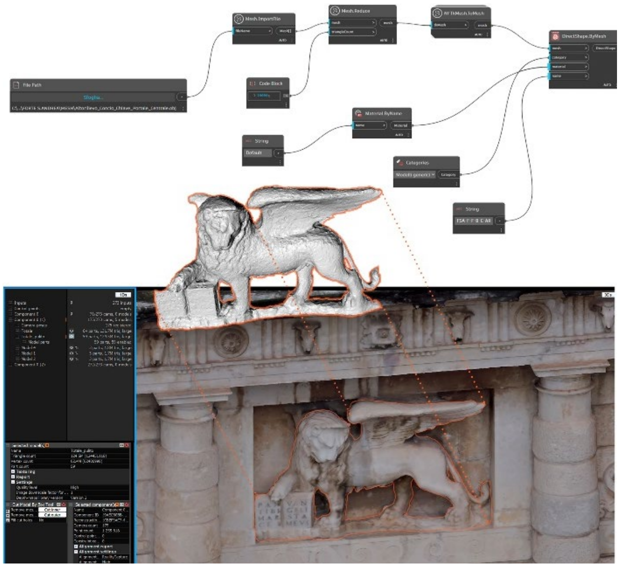


Figure 7. *Characterisati*on. Integration of sculptural elements through mesh management using VPL. *Porta di Terraferma,* Zadar.

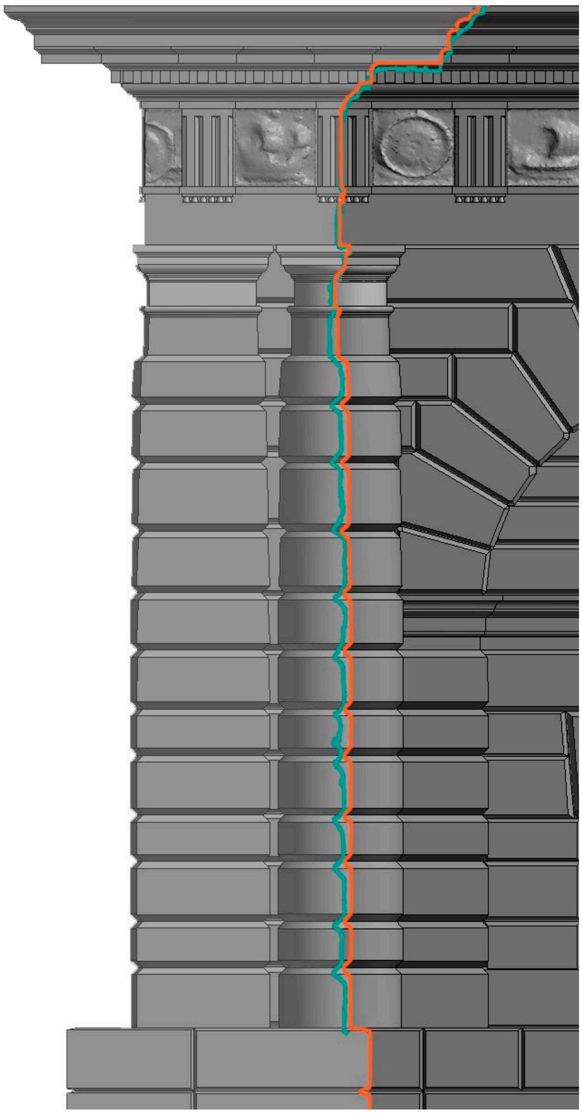


Figure 8. *Characterisati*on. Morphometric comparison of the HBIM model section (orange) adapted to the surveyed geometry (green). Gate of *St. Andrea Fortress*.

approach ensured spatial and topological control over the mesh placement, while maintaining a clear distinction between parametric geometries and non-parametric sculptural or decorative components.

Integrating such plastic elements − statues, reliefs, coats of arms and other decorations − enriched the model with a level of detail consistent with the formal and symbolic complexity of the architectures under study. Their inclusion represented an essential step in the model's characterisation, allowing for expressing each portal's specific identity and the fortified architecture as a whole.

Based on the analysis, developing customised parametric objects, through the controlled use of dimensional and typological parameters, significantly streamlined the modelling process. This enabled each element to be directly adapted to the point cloud by adjusting the parameters of the families, without the need for manual modelling operations.

4. Results and future developments

The proposed methodology has proven highly effective in ensuring a level of detail and accuracy consistent with the complexity of the analysed architectural elements, while enabling a dynamic and flexible management of geometric entities and the associated information. This integrated approach allowed for a deeper understanding of the interrelationships between the various architectural components, facilitating the interpretation of their features and the comparison between ideal models and surveyed reality.

One of the most significant outcomes lies in the ability to formalise structured information models capable of effectively describing the case studies examined, with content that can be adapted and reused in related projects. This approach contributes to developing a shared and interoperable library of architectural components, aimed at supporting the understanding and valorisation of the entire fortified architectural *corpus* of the Veronese engineer.

In this regard, the preliminary study of Sanmicheli's compositional principles enabled the structuring of parametric families based on his design system, generating a parametric framework that allowed for an optimised modelling process.

In the broader context of historical heritage modelling, analysing past geometric and proportional rules remains an essential phase in developing parametric libraries, helping to address the complex interaction between contemporary digital languages and historical compositional grammar.

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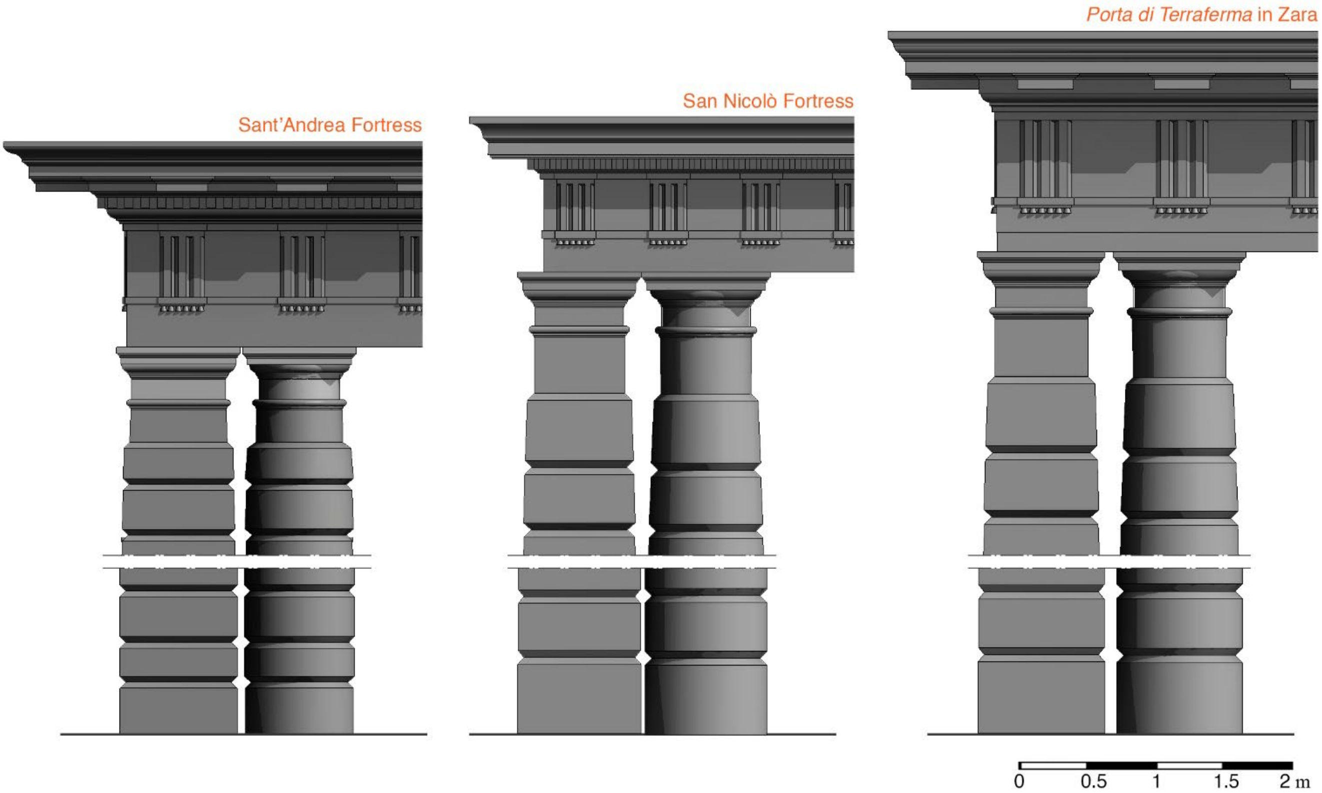

Figure 9. Metric and compositional comparison of the HBIM models of the three portals: the Gate of *Sant'Andrea Fortress* in Venice, the Gate of *San Nicolò Fortress* in Šibenik, and *Porta di Terraferma* in Zadar.

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