The Significance of Porches in Urban Applications: A Method for Automated Modeling and Integration

Yuwei Cao [1], Daniele Treccani [1], Andrea Adami [1],

[1] Department of Architecture, Built environment and Construction Engineering, Politecnico di Milano,
UNESCO Research Lab, Mantova Campus, Piazza C. D'Arco, 3, 20133, Mantova, Italy
(yuwei.cao, daniele.treccani, andrea.adami)@polimi.it

Keywords: Porches, Citygml, Space Modeling, Cultural Heritage, Point Cloud Processing, Classification

Abstract

Porches, as defined by the Art & Architecture Thesaurus, serve as vital transitional spaces linking indoor and outdoor environments. Despite their historical and contemporary significance, porches lack explicit representation in prevalent standards like CityGML and IndoorGML, posing challenges for comprehensive spatial modeling and its application. This paper proposes a method for modeling porches that aligns with the existing OGC standard CityGML 3.0, ensuring accuracy and compatibility. Drawing upon geomatics techniques, the method aims to bridge the gap in representing these spaces, critical for applications such as navigation systems, urban planning, and energy simulations. By integrating geometric, machine learning, and informative modeling approaches, this method seeks to provide a robust foundation for various practical applications. The paper outlines a comprehensive state-of-the-art review, describes the proposed method from digitalization to random forest (RF)-based point cloud classification and vectorization, presents case studies and results, and offers critical discussions and conclusions. Through this endeavor, the paper contributes to enhancing the representation and understanding of porches within the digital spatial landscape.

1. Introduction

The Art & Architecture Thesaurus defines porches as roofed, open-sided spaces adjacent to buildings, primarily sheltering entrances or serving as living areas. They have long held a distinctive place in the architectural landscape, serving as transitional spaces connecting the indoors and the outdoors. Those architectural elements embody a unique blend of shelter, connection, and communal significance. They are often found in historic districts, but their presence is not limited to the past, in fact, porches can also be observed in modern environments. These spaces act as buffers between private interiors and public exteriors, serving as a place for social interactions. Furthermore, porches contribute significantly to seamless navigation and wayfinding, acting as distinctive landmarks that guide individuals through urban spaces. Their recognizable and often unique architectural features facilitate smooth transitions, enhancing the overall navigational experience for residents and visitors alike. Lastly, porches provide practical benefits, especially in varying weather conditions. During the heat of summer, they offer much-needed shade, creating comfortable outdoor environments. On the other hand, in winter, porches provide protection from the elements, making them a preferred path for pedestrian movements within the city.

For disciplines concerned with the study of mobility and the navigation of spaces, porches can have a fundamental place as a connection between indoor and outdoor spaces. In particular, indoor-outdoor seamless modeling and navigation (Claridades and Lee, 2021; Yan et al., 2021) involve creating a cohesive experience for individuals moving between interior and exterior spaces. The importance lies in providing a smooth and integrated transition, enhancing user experiences in various contexts such as urban planning, architecture, and navigation systems. This approach ensures continuity in spatial representation, facilitating more intuitive navigation and wayfinding across indoor and outdoor environments. It is crucial for applications like smart cities, facility management, and location-based services, where users often navigate through mixed-use spaces. The seamless integration fosters efficiency, accessibility, and a holistic understanding of spatial surroundings.

Regarding the role of porches as transitional spaces connecting indoor and outdoor environments, the definition and representation of porches might involve both indoor and outdoor characteristics. The Geographic Markup Languages for City (CityGML) 3.0 specification (Kutzner et al., 2020; Kolbe et al., 2021) stands as the prevalent standard data model for representing 3D city models at different Levels of Detail (LoD). The CityGML standard focuses on higher-level urban elements and it includes the representation for elements like "wall," "roof", "window," and "door" in LoD2 - 3. However, porches, often integral to buildings, lack of explicit representation. Given that CityGML enables the modeling of different architectural elements within buildings, it provides a suitable framework for representing porches. Through the inclusion of geometry, semantic, and topological relations, CityGML can effectively describe the shape, function, purpose, and relationships of the porches attached to buildings. On the other hand, IndoorGML 1.1 (Lee et al., 2020) is a standard designed to support the modeling of indoor spaces. IndoorGML excels in modeling interior structures, such as "floors," "walls," "doors," and "stairs," and the ability to model connectivity and relationships between these features. For instance, Lee et al. (2020) introduced the IndoorGML to be explicitly dedicated to indoor 3D navigation. While IndoorGML is primarily designed for indoor spaces, it does not provide explicit guidance on the representation of porches.

Within the presented context, where porches are not completely represented by OGC (Open Geospatial Consortium) standards, and given the ambiguity of porches as a space which can be considered indoor while being on the outdoor, and viceversa, they act as a transitional space which have great importance for many applications and which require further study. Therefore, the purpose of this paper is to define a semi-automatic method that allows modeling such elements with the appropriate accuracies and compatible with existing OGC standards. The results could be the bases for many applications, such as navigation, city management, energy simulations.

Furthermore, for a proper geometric survey of porches there are various possibilities, given by geomatics techniques. However, not all of them allow for the same accuracy, or the same ability to fully capture and survey the areas of interest. Also, it is always necessary to remember that digitization is also related to the scale of the survey and the architectural and urban approach, which lead to different results. For this reason, this article also becomes an opportunity to discuss the most appropriate geomatics techniques for a porch survey, relating it to objectives and accuracy.

The paper is organized as follows. Section 2 outlines more clearly what a porch is and how it can be defined, including techniques for digitising it. Section 3 describes the approach and methods used for porch surveys in this article. Section 4 describes the the method used in this article, from classification to vectorisation. Section 5 presents the results applied to a case study. Section 6 is devoted to discussions and conclusions.

2. Peculiarities of porches

2.1 Definitions of "porch"

The definition of a space is the first step, fundamental for its management. Regardless of the context - architectural or urban, survey or design- correctly describing an environment means knowing it and sharing its characteristics with other users through shared standards and languages. Many spaces are clearly defined from the geometrical point of view and the functional point of view, but some cases are located on the edge, on the threshold between two very different characteristics.

Porches (or portico, arcade, or colonnade according to the specific declination of the same spatial concept) is a significant example of these un-well-defined spaces. They play a key role in connecting indoor and outdoor spaces without being completely inside or outside. As shown in Table 1, they are also very rich in different meanings according to the discipline of architecture, urban planning, and city management. In the face of this complexity, it is even more important to be able to find shared definitions to enable spatial geodata to be used across multiple platforms and among different users. This section highlights the importance of porches in many geospatial definitions, from the traditional bi-dimensional representation of cartography to 3D and OGC standards such as CityGML 3.0.

Source s	**Definitions**
The Art & Architecture Thesaurus – AAT (Getty Vocabulary, 2017)	Use to designate roofed spaces, open along two or more sides and adjunct to a building, commonly serving either to shelter an entrance or used as living space.
Dictionary of Architecture and Construction (Harris, 2006)	An exterior structure that extends along the outside of a building; usually roofed and generally open-sided, but may also be partially enclosed, screened, or glass-enclosed; it is often an addition to the main structure.
OpenStreeMap	A porch is a covered area adjoining an entrance to a building and usually having a separate roof.
WordNet (Fellbaum, 1998)	A structure attached to the exterior of a building often forming a covered entrance
Oxford Dictionary (Pearsall, 2010)	A covered shelter projecting in front of the entrance of a building

Table 1. Different definitions of porches in different sources.

2.2 Porches: a spatial element with many purposes

Porches are architectural elements that can be considered "ambiguous" in that they connect very different concepts. First and foremost, they mark the transition between indoor and outdoor spaces. And so, in some way, they also reflect the distinction between private and public.

However, there are peculiar aspects that make these spaces very interesting and used throughout the history of architecture. Known as early as Greek and Roman times, porticoes have been used in all periods and continue to be used today; with different forms and materials, they still retain their main characteristics. They are in fact, open spaces, but covered with a roof, which thus protect against sun and rain. According to this, they are also connected with the country's climate; in some cases, they become distinctive features of a city. This is the case of Bologna, who was inscribed in the World Heritage List of UNESCO in 2021 as the City of Porticoes. But in all of Europe, they constitute an architectural element of the urban landscape. They are public spaces but with a more "intimate" and private character, almost an antechamber to the actual dwelling.

These characteristics are even more evident when considering the concepts of scale and the disciplines involved in them. On an architectural level, they are very refined spaces that are always designed with care and detail: in ancient times, they were covered by vaults, often frescoed, or wooden ceilings, sometimes decorated. At the urban level, on the other hand, they are resources for pedestrian traffic as well as for public activities such as town markets.

2.3 Porches digitization

The most challenging aspect of defining porches is their ontological nature. It is crucial to discover effective descriptions that can be shared and applied according to the application area.

A digital survey does not reveal technical critical elements for their geometric knowledge. Anyway, digitization is also connected to the scale of the survey and the architectural and urban approach, which lead to different results.

The approach used for urban-oriented mapping, such as large-scale mapping (since porches are not even represented in small-scale mapping), is from the top, using almost equally LiDAR instruments or photogrammetry techniques. Generally, data are acquired from aerial platforms with the advantage of being able to acquire large portions of the territory quickly and without obstacles. Regardless of the technique chosen, the top-down acquisition is always partial. The ground connection of the walls can be acquired only if the street's width, height of flight, and angle of acquisition are well-designed and balanced. But the oncoming representation is suitable only for a planimetric approach. Acquiring coverage in a top-down approach remains impossible in any case. Consequently, there is still a gap in knowledge, which is justified by the purpose (urban use) and scale of representation.

Moving to the architectural survey, the porches are spaces that are easier to digitize, at least in the acquisition phase. They can be treated as rooms emptied of their walls but with a clear and defined configuration. In this way, the acquisition if not only of the walls (and columns) but also of the roof, whatever it is. The result is a complete description of all parts of the porches, with eventual specific focuses on the decorative aspects of the vaults or decorated ceiling (Apollonio et al., 2014).

The analysis of two-dimensional architectural surveys of porches is excluded from this research because it is impossible to find, in them, a unified coding and shared standardization. Instead, it is considered important to analyze two-dimensional cartographic representations to understand whether porches are represented, what data are included, and how they are classified.

A first preliminary observation concerns, obviously, the scale of representation. Small to medium-scale maps do not include porches among the elements to be represented. And this choice is due not only to the scale of representation, which would make it impossible to draw them, but also to the purpose of cartographic representation: the management of a vast territory. On the other hand, when moving to medium-large scales (indicatively up to 1:1000), the porch datum is fundamental precisely because the scope of intervention is the urban environment.

A second observation is related to the standardization of two-dimensional data. The existence of a tradition of cartographic representation has made the need for standardization perhaps less compelling than in other areas. However, work is being done internationally to ensure the homogeneity of the data. The cartographic representation created by OpenStreetMap (OSM) and the GeoTopographic Database (DBGT) of the Lombardy Region (Italy) will be analyzed as an example of a supranational approach.

3. Survey of Porches

To reach a complete digitization of porches for their 3D representation both in GML context, or other representations, the top-down approach is not enough. As said before, acquiring from above, in fact, risks missing many important elements such as the ground attachment of walls (to define the depth of porches), the porch roof (flat or vaulted), and sometimes even the pavement (thus losing information about the walking height). Thus, a "bottom-up," street-level approach is appropriate and necessary to complete the collection of information.

Geomatics today offers many possibilities, but undoubtedly the main distinction is between a static and a dynamic survey. The first case mainly involves the use of the TLS, which, despite its multiplicity of tools, accessories and characteristics, makes it possible to achieve good accuracies for the architectural and urban sphere and excellent coverage of the surfaces to be surveyed, through a well-structured, high-density point cloud. In contrast, this approach suffers from operability. Acquisition times are much longer, and operations also require more attention (just think of the presence of people hindering static acquisition).

The other possibility is a Mobile Mapping System (MMS). Again, it is necessary to choose between different methods and instruments (hand-held, backpacks, on-vehicle). In any case, the common characteristics of all these are speed of acquisition and ease in operational steps. The negative aspects, on the other hand, concern accuracy and point density. Another effect to consider is the geometric distribution of points. In fact, some mobile systems, depending on the arrangement of sensors, produce a point cloud with the points distributed aligned on lines that are the combined result of user movement and rotation of the LiDAR sensor, sometimes called “spaghetti effect”. This effect is definitely anti-aesthetic in the navigation of the cloud, but creates no real problems in its use, especially at the urban scale. Finally, it should be noted that although it is always possible to convert data from a local reference system to a national reference system, mobile systems can generally provide the data in the cartographic reference system immediately, while TLS systems usually require topographic or GNSS support.

In this research, the two approaches have been tested and compared on a portion of a porch within Mantova city (Italy). The first acquisition was made by the TLS Leica RTC360. a portion of the porch corresponding to two arches was surveyed in 6 scans made with an average resolution of 6 mm at 10 m. Acquisition times were 15 minutes and post processing took 30 minutes. In this test, the single scans were aligned in Cyclone Register 360 with only a ICP approach without a topographic reference network.

The second acquisition was made by the Stonex X120 GO SLAM, a hand-held mapping system equipped with a digital camera that can mount also a RTK receiver. The acquisition time, in this case, was very short (5 minutes) as the data was acquired by a simple walk in the area, paying attention to pass under the porch and on the street to see both the sides of the columns.

Table 2 summarizes all the main data concerning the two acquisitions with different instruments. Apart from the total number of points, it is important to consider also the point density of the two cases. The density of TLS is very high compared to the ones of MMS as evident from Figure 1

	TLS	MMS
Total amount of points	220 million	14 million
Average Point density on the floor	120000 pts/m^2	3500 pts/m^2
Average Point density on the upper part of façade (10 m height)	4000 pts/m^2	1000 pts/m^2

Table 2 Comparison between point densities on crucial surfaces of porch spaces, surveyed with TLS and MMS.

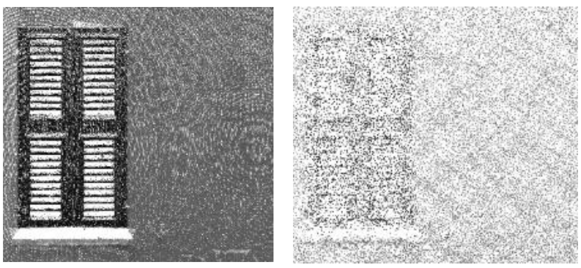

Figure 1. the diverse density of points on the façade (near a closed window) is evident in these two images, which are on the same scale (TLS on the left and MMS on the right)

Apart from the different densities, it is important to keep clear in mind the purpose of the digitization and, above all, the scale of representation. Generally, if the goal is the urban scale, and a schematic representation, mobile data is surely suitable for it. And, in this case, time saving is a very beneficial element, especially if the work is very extensive.

https://doi.org/10.5194/isprs-archives-XLVIII-4-W11-2024-9-2024 | © Author(s) 2024. CC BY 4.0 License.

4. Method

4.1 Overview of the method

The purpose of the method is to generate a vector file representing porches in the urban environment. The method is based on a point cloud of the urban environment to be studied. The point cloud should have been acquired from the ground preferably and with a sufficient point density to correctly identify the characteristic elements of the porch. First, a machine learning approach is used to classify the point clouds according to classes defined by the main elements of the porches. Secondly, based on the classification result and in compliance with OGC standards, the porches and their main components are vectorized in an attempt to conform to CityGML LOD 0, 1, and 2.

4.2 Porch classification

In this work, we present a random forest (RF) classifier that uses geometric features to classify the porch point clouds. Unlike deep learning (DL) methods, the RF classifier does not require a significant amount of manually annotated data (Cao et al., 2022). Instead, it focuses on distinctive geometric features that highlight the structure of the porch point cloud within a certain radius of the points. These geometric features, which are related to the dimensions of the elements, allow the classifier to distinguish the discontinuities between porch elements.

The classification process consists of four steps: i) extraction of geometric features based on the covariance matrix for the porches; ii) manual segmentation of a part of the porches to be used as training and evaluation set; iii) training of the RF classifier; iv) input of the dataset to be classified together with the computed covariance features to the trained model to obtain the final prediction.

The geometric covariance features are calculated for radii ranging from 0.05 m to 0.4 m, with increments of 0.05 m: i) Planarity ii) Anisotropy iii) Verticality iv) Surface variation v) Linearity vi) Sphericity vii) Omnivariance. In addition, according to the methods in (Grilli et al., 2019; Teruggi et al., 2020), the z coordinate of each point is taken into account, geometric features planarity and linearity are also calculated for a radius of 0.8 m. Figure 2 shows some examples of the extracted geometric features.

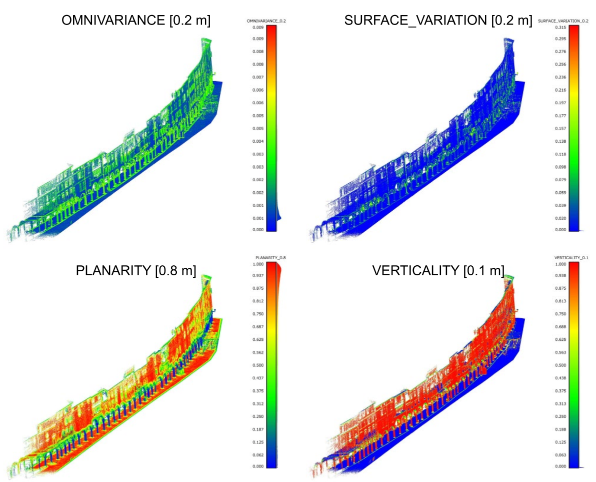

Figure 2. Examples of computed covariance features on porches. The number inside the square brackets indicates the radius of the searching neighborhood.

In order to represent the structural components of porches, the categories "floor", "façade", "column", "arch", "vault", "openings", and "stairs" are examined in this study.

4.3 Vectorization

We produced three-dimensional (3D) models of porches at various levels of detail (LoD), ranging from LoD0 to LoD2, in accordance with the guidelines of CityGML 3.0 (Kutzner et al. 2020), which enables the modelling of buildings at four levels: LoD0, LoD1, LoD2, and LoD3. Although the constructed building model can be most accurately represented at the highest level of detail (LoD3), doing so requires more complex reconstruction from multiple data sources such as airborne LiDAR point clouds and MMS point clouds (Peters et al., 2022). In this study, we focus on the reconstruction of LoD0, LoD1, and LoD2 from available data sources (OSM, DBGT, and acquired point clouds).

The OSM and DBGT datasets were the two primary sources of the geodata, both of them provide 2D building footprints in their datasets. Specifically, building footprints were exported for the chosen study area in both datasets. Then the building footprints were employed to create the porch models at LoD0.

In these datasets, porches are represented differently. In OSM, porches are represented as "pathway" features, the line representation of porches in OSM uses two tags "layer= -1" and "covered=yes" to describe the vertical relationships between these buildings and porches, which are overlapping features in the LoD0 representation. In addition, in DBGT, they represent the parts of buildings above the porches using building units as the representation in the footprints (see Fig. 6b). In this way, the porches could be found within the DBGT as void spaces, but they are not modelled and well represented. To represent these two overlapping features in 2D, we create another vector layer to represent them. Specifically, since we consider the porches to be a space in the building, we use a polygon to represent them for this study. Then, following the OSM method, we add a "layer" attribute to porch layer to represent the vertical relationship between different features. In this way, "layer= -1" is set for the porch and the vertical ordering of porch and the part of building above it is established by this attribute.

An extrusion approach was used to create 3D building models in LoD1. The 2D building footprints from the DBGT dataset were extruded to a single height to create 3D volumetric models for each building. Building heights could be obtained from airborne laser scanning (ALS) data (Ledoux et al., 2021) or cadastral databases that provided the average elevation of all points or roof heights within a footprint. In the absence of ALS data, building height information was obtained from the DBGT. The "UN_VOL_AV" field describes the minimum height per unit of building volumes. In our work, building height is determined by the maximum height of the units in each building footprint to represent a flat roof. For the porch representation, since it is a semi-closed space (Yan et al., 2021), where it is bounded by virtual boundaries, we use void spaces to represent porches in the LoD1.

For LoD2 modeling, we first use the footprints in DBGT dataset to enrich the roof details of buildings based on the LoD1 model. Specifically, the "UN_VOL_AV" field provides the height information of the lower part of each roof segment, allowing us to model roofs with greater accuracy following the extrusion method in the modeling of LoD1 model.

For the porches, the detailed geometric shape and precise location of the columns are required in LoD2. To obtain such information, we first extracted column objects from the point clouds. Column features were manually digitized according to the location and shape in the point clouds using QGIS software (see Fig. 3). Then we calculate the porch height by calculating the cloud-to-cloud distance of the ground and vault point clouds along the Z dimension. The maximum distance from the top of the vault to the ground is used as the porch height.

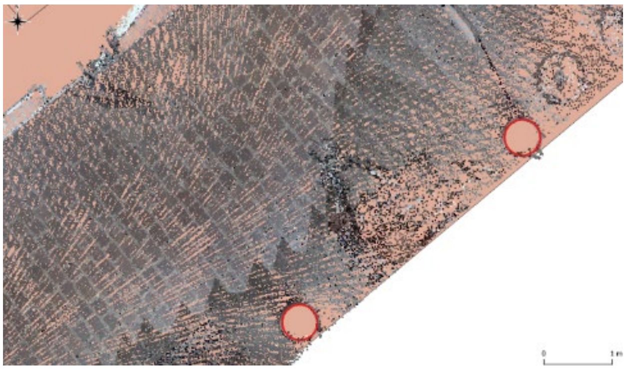

Figure 3. Illustration of manually digitalization of the column features. The columns are represented by polygons in QGIS using red outline for visualisation of both columns and its correspondence with the point cloud.

5. Case study and first results

The proposed method was tested on a real case study: an urban environment in a portion (see Fig. 9b) of the city of Mantova, in northern Italy. The city has been a UNESCO site since 2008, and its urban layout boasts the presence of numerous porticos that alternate with the various squares and connect the city's main monuments and buildings with each other, making it a fundamental meeting place as well as a preferred connection for the city's users.

The city's porticoes as well as urban areas were surveyed using different instruments, including portable mobile mapping systems (see Fig. 4) and TLS. As previously stated, MMS data could be suitable for the purpose of urban management, so our tests were made only on MMS point clouds.

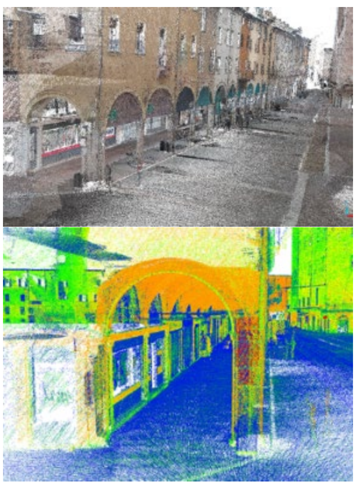

Figure 4. Point clouds of porches in Mantova , surveyed using STONEX X120 Go.

The classification performed in the experiment uses the RF classifier available in the Scikit-learn Python library (version 1.4.2). The number of decision trees and the number of variables to be selected and tested for the best split when growing the trees were set to 200 and "None", respectively. This allows the creation of forest trees. A prediction is obtained from each tree, and the best solution is selected by voting among them. A specific RF classifier was trained for the porticoes of Mantova. Figure 5 shows the training sets (manually annotated parts) used to train the classifier.

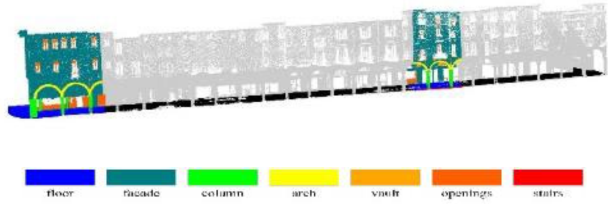

Figure 5. Examples of manually labeled training and evaluation data. Classes are floor, façade, column, arch, vault, openings, and stairs.

The ML-based approach is successful in classifying the considered scenes. In particular, the accuracy reaches up to 0.882, and the f1-score reaches 0.881 for the portico area. The qualitative results of the semantic segmentations are shown in Fig. 6. We can see that the RF classifier produces a smooth and accurate result.

The ML-based method shows robust performance in the porch area, highlighting its ability to effectively classify the porch point clouds. However, the results of the ML-based method are strictly dependent on the quality of the geometric features computed on the point cloud and fed to the RF classifier. For example, the façade close to the porch has many openings (windows and doors) made by glass, which results in holes in the point clouds and poor geometric feature computation results. Errors are concentrated in those parts of the point cloud where the point cloud is particularly sparse.

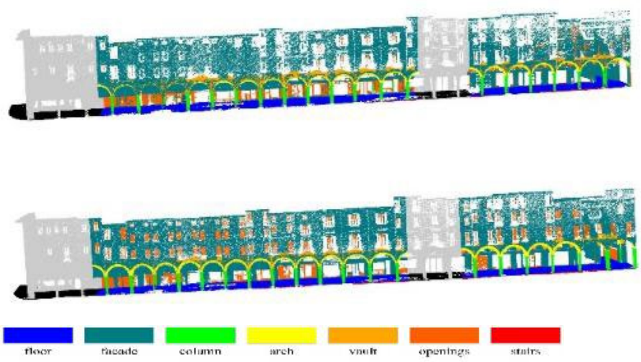

Figure 6. Classification result (top) and GT (bottom).

The results of vectorization in different LoDs are shown in Figures 7-9. For LoD0, as seen in Fig. 7, compared to the representation of porches in OSM (Fig. 7a) and DBGT (Fig. 7b), our representation can clearly show the location and relationship between porches and buildings. For the representation of porches in LoD1 (see Fig. 8), since LoD1 should be the solid of the whole building, the porches are ignored in such representation in the CityGML 3.0 specification (Fig. 8a). To represent this type of semi-closed spaces (Yan et al., 2021), we represent them using void spaces (see Fig. 8b). In LoD2, the boundaries of the porches are represented as virtual bounded boxes. In addition, the columns are visualized according to their locations and shapes in the point cloud data. As discussed in Section 4, our focus is on the representation of porches, so the roof portions (see Fig. 9b) of buildings are not included in the LoD2 representation.

Figure 7. Example of porches at LoD0 using different representations: line in OpenStreetMap (OSM) (a) *vs.* polygon of façade over porch in DataBase GeoTopografico (DBGT) (b) *vs.* ours (c).

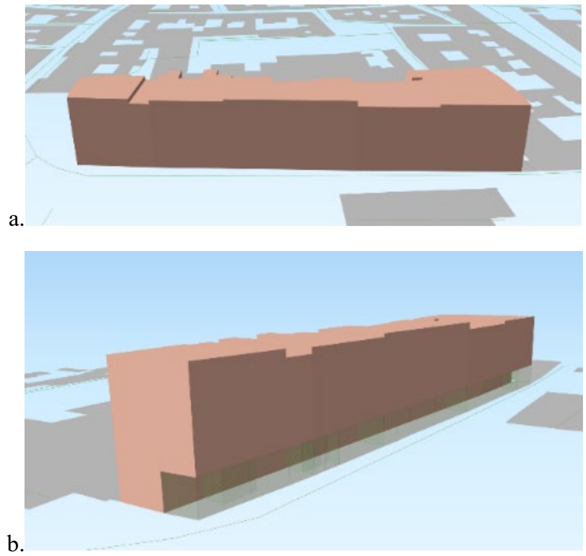

Figure 8. An example of representing buildings at LoD1 (a), an illustration of using void space to represent porches at LoD1 (b), the map generated using the qgis2threejs plugin in QGIS.

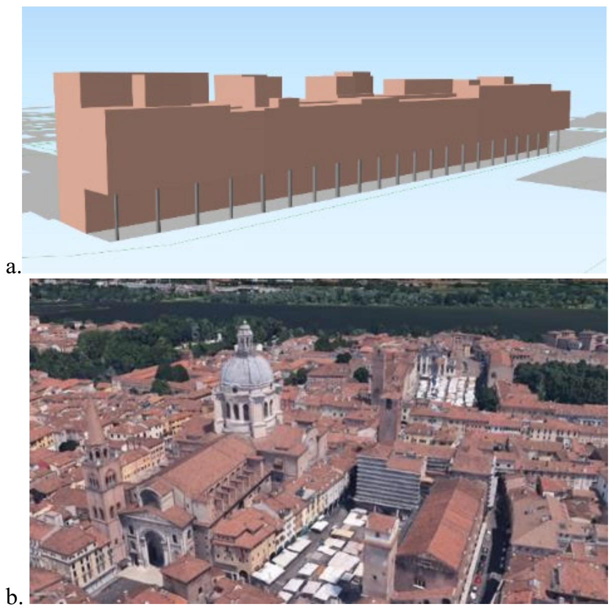

Figure 9. Representations of the porches at LoD2 (a) and the research area on Google Maps (b). Shapes and positions of the columns are manually extracted from the point cloud collected using the Mobile Mapping System (MMS).

6. Discussion and conclusions

Porches are an important element for a city, they are a meeting point for citizens, a privileged place for pedestrian and non-pedestrian mobility, and a place to find shelter in various weather conditions. Moreover, these elements are peculiar because porches seem to be a rather unique configuration of the indoor/outdoor environment, as they represent a space of transition and at the same time of union between indoors and outdoors, between public and private.

The paper proposed a method for the proper geometric survey of porches within urban environments and the analysis and modeling of such spaces. The method developed and tested on a real case study, the city of Mantova, allows for the automatic classification of survey data, identifying the main elements of the porches to model the space. The classified point cloud was then exploited together with OSM data and the DBGT of the case study area in order to model porches at different LoDs (0-2). The preliminary results shown in this article illustrate a procedure showing a partially automatic modeling of porches, following the LoDs as specified by OGC standards.

From what has been shown, it can be deduced that MMS systems can be adequate for the analysis of urban areas and that, although they feature much lower densities of points on the surveyed objects than other tools (e.g., TLS), they produce point clouds that are nevertheless adequate for classification and vectorialization processes. In our case then, the joint use of point clouds and map data (OSM and DBGT) allowed us to adequately and completely model the porches, which were considered as empty spaces, but nevertheless modeled with three-dimensional elements. The point cloud classification phase was automated and based on an RF, while the modeling phase is currently almost completely manual.

The resulting file could be a solid base for many applications, such as the calculation of paths for seamless indoor-outdoor modeling, the generation of 3D city models to perform energy simulations, or for cartographic purposes. Furthermore, the analysis shows the importance of porches as transitional spaces that should be addressed by OGC standards.

For future research, we plan to 1) improve the classification results; 2) use the classification results to fully automatically reconstruct the porch models at LoD3 based on deep learning, so that the model includes more complex and complete structures of the porches, such as arches and vaults.

Acknowledgements

The authors would like to thank STONEX for providing their STONEX X120 GO instrument and for their assistance in raw data processing.

References

Apollonio, F.I., Gaiani, M., Fallavollita, F., Ballabeni, M., Zheng, S. 2014. Bologna Porticoes Project: 3D Reality-Based Models for the Management of a Wide-Spread Architectural Heritage Site. In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, AY., Quak, E. (eds) Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2014. Lecture Notes in Computer Science, vol 8740. Springer, Cham. https://doi.org/10.1007/978-3-319-13695-0_49.

Cao, Y., Teruggi, S., Fassi, F., & Scaioni, M. 2022. A comprehensive understanding of machine learning and deep learning methods for 3D architectural cultural heritage point cloud semantic segmentation. In Communications in computer and information science (pp. 329–341). https://doi.org/10.1007/978-3-031-17439-1_24.

Claridades, A.R.C. and Lee, J., 2021. Defining a model for integrating indoor and outdoor network data to support seamless navigation applications. ISPRS International Journal of Geo-Information, 10(8), 565. https://doi.org/10.3390/ijgi10080565.

Fellbaum, C., 1998. WordNet: An Electronic Lexical Database. Cambridge, MA: MIT Press. https://wordnet.princeton.edu/. (Accessed 30-04-2024).

Getty Research, 2017. Art & Architecture Thesaurus, https://www.getty.edu/research/tools/vocabularies/aat/. (Accessed 30-04-2024).

Grilli, E., Farella, E. M., Torresani, A., and Remondino, F. 2019. Geometric features analysis for the classification of cultural heritage point clouds, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W15, 541–548, https://doi.org/10.5194/isprs-archives-XLII-2-W15-541-2019.

Harris, C. M., 2006. Dictionary of Architecture and Construction. (ISBN. 0071589015; 4th ed.). McGrow Hill. https://archive.org/details/dictionary-of-architecture-and-construction.

Kolbe, TH., Kutzner, T., Smyth, ST., Nagel C., Roensdorf C., Heazel C., OGC City Geography Markup Language (CityGML): Conceptual Model Standard, 2021. http://www.opengis.net/doc/IS/CityGML-1/3.0 (Accessed 30 January 2023).

Kutzner, T., Chaturvedi, K., Kolbe, T. H., 2020. CityGML 3.0: New Functions Open Up New Applications. PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 88(1), 43–61. https://doi.org/10.1007/s41064-020-00095-z.

Ledoux, H., Biljecki, F., Dukai, B., Kumar, K., Peters, R., Stoter, J., Commandeur, T., 2021. 3dfier: Automatic reconstruction of 3D city models. Journal of Open Source Software 6, 2866. doi:10.21105/joss.02866.

Lee, J., Li, K.-J., Zlatanova S., Kolbe, TH., Nagel, C., Becker, T., Kang, H.-Y., OGC® IndoorGML 1.1, 2020. http://www.opengis.net/doc/IS/indoorgml/1.1 (Accessed 30 January 2024).

OpenStreetMap Wiki. OpenStreetMap Wiki. https://wiki.openstreetmap.org/wiki/Item:Q16513. (Accessed 30-04-2024).

Pearsall, J., Hanks, P., Soanes, C., & Stevenson, A. 2010. Oxford Dictionary of English. In Oxford University Press eBooks. https://doi.org/10.1093/acref/9780199571123.001.0001.

Peters, R., Dukai, B., Vitalis, S., Van Liempt, J., & Stoter, J. 2022. Automated 3D reconstruction of LOD2 and LOD1 models for all 10 million buildings of the Netherlands. Photogrammetric Engineering and Remote Sensing, 88(3), 165–170. https://doi.org/10.14358/pers.21-00032r2.

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, 12(16), 2598. https://doi.org/10.3390/rs12162598.

Yan, J., Zlatanova, S. and Diakité, A., 2021. A unified 3d space-based navigation model for seamless navigation in indoor and outdoor. International Journal of Digital Earth, 14(8), pp.985-1003. https://doi.org/10.1080/17538947.2021.1913522.