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Cluster Analysis as a Basis for Local Masonry Typology

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Abstract. Detailed knowledge of local construction features plays a remarkable role in examining and modelling historic buildings, both in the field of mechanical and energy performances. This study proposes a standard procedure for local masonry typology and explores the use of a statistical tool - cluster analysis - to define historic masonry types in local areas.

The purpose of using cluster analysis as a tool for local masonry typology is to reduce the subjective influence of the observer. Consequently, the accuracy of local context analysis can be maintained, but using a homogeneous typology structure, intended as a general instrument for the detailed thermal and mechanical analysis of historic buildings.

The proposed method was applied to four local contexts, namely the historic centers of four small cities in Sicily: Castel di Lucio, Patti, Santo Stefano di Camastra, and Tusa. All masonry walls with visible arrangement were examined in the case studies, thus collecting a dataset of 157 walls.

Cluster analysis was carried out through the R software, considering each examined wall as an observation. Gower distance was selected as the distance metric. Partitioning Around Medoids algorithm (PAM) and the average silhouette width were used.

Clusters have been identified both analyzing each case study and the entire dataset. In the latter, the analysis resulted in three homogeneous clusters, with average silhouette width equal to 0.46. Distribution of relevant construction features (average dimensions of masonry units and mortar joints, MQI) in the three clusters of the overall dataset suggest classification based on cluster analysis is appropriate to the technical examination of masonry.

Keywords: Masonry typology · Local context · Cluster analysis · MQI · Historic building

1 Introduction

Compatibility with the historic building, both in the case of maintenance, restoration, and performance improvement, is based on the effort to know the transformations, the aesthetic and material features, and the technical components, of the building. This

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process of analysis requires a case-by-case approach, but it also includes the historic construction practices, which were peculiar to the geographic, cultural, and economic context where the building is located.

The Italian Handbooks for historic centers - as [1] and [2] - demonstrate the importance that the recurring construction features of local areas have both in analyzing characteristics of the specific building and designing actions for its conservation and compatible use.

In the field of energy efficiency, the role of local recurring features is remarkable in examining and modelling the thermal envelope, which is often heterogeneous in historic buildings. The difficulty to characterize the historic thermal envelope is mainly related to discontinuities of masonry walls, caused by historic transformations and by the variety of materials, which were used in the same area but in different periods of construction. This heterogeneity is frequently combined with the presence of not removable coverings, as decorated plasters, concealing the masonry work.

Together with the characterization of local construction materials, detailed thermal analysis and modelling of the single building may be effectively supported by local masonry typology. Focusing on the recurrent construction features of historic walls in circumscribed areas, local masonry typology is useful to integrate the information collected in the building, thus reducing destructive tests while improving the model accuracy.

The construction features, which can be examined in depth by local masonry typology, are also relevant to the mechanical analysis of historic structures. The significance, that detailed study of local construction techniques proved to have in this field [3], suggests that the method is suitable to support a combined analysis of structural and energy performances.

Masonry typology is based on detection and analysis of wall construction characteristics, followed by identification of recurring features. Hierarchy is decided for the recurring characteristics according to the scope of the study, and masonry types are defined consequently. Since the procedure is based on survey and comparison of inspected walls, the identification of types is necessarily influenced by the observer, especially if the analysis is limited to a single local context instead of different areas.

The research exposed in this paper proposes a standard procedure for local masonry typology and explores the use of a statistical tool - cluster analysis - to define the historic masonry types in local areas. The use of cluster analysis has increased in the classification of a building stock in the perspective of its renovation [4, 5] as well as in the development of building energy models on the urban scale [6]. Indeed, cluster analysis allows to examine several building features in parallel, and to improve the precision of segmentation [7].

In this study, the purpose of cluster analysis is reducing the subjective influence of the analyst in the results of masonry typology. In this way the accuracy, which is peculiar to the analysis of local contexts, will be maintained, but a homogeneous typology structure will be used, intended as a general instrument for the detailed thermal and mechanical analysis of historic buildings.

2 State of the Art

Masonry typology is well established in the performance assessment of historic masonry. This methodology is founded on the systematic analysis of construction features, such as the materials used, the geometry and arrangement of wall units, the construction of details as corners and masonry frames of openings. These characteristics are crucial to assessing both the mechanical and thermal performances of the wall. In this perspective, masonry typology is able to mitigate the difficulties caused, on the one side, by the geographical and technical variety of masonry, and on the other side, by the heterogeneity of construction components in the same building.

Masonry typology is largely employed in studies [3] and practice [8, 9] on the mechanical performances of historic walls. Special attention is paid to the development of methods for the accurate modelling of the wall [10], which are necessary to the mechanical characterization of masonry types [10, 11]. Therefore, relation between masonry type and mechanical properties is a relevant research topic [10], with a remarkable contribution from the method of Masonry Quality Index (MQI) [12, 13].

The method of MQI employs data collected through the visual inspection of the wall. The mechanical parameters of the wall and its level of safety against seismic actions are assessed by means of qualitative criteria, referred to masonry materials, conservation state and construction features of the wall arrangement.

The main construction details, which are considered in the calculation of MQI, also determine the actual thermal performance (notably, U-value) of the historic wall, especially if compact stones are used, with a significant difference in λ-value compared to mortar. Consequently, a method has been proposed to examine the effect of local recurring features on the thermal performance of historic walls, and to combine the qualitative assessment of their thermal and mechanical performances [14].

If masonry typology is used to manage the construction variety of masonry with the aim of improving the accuracy of current models and assessments, this accuracy cannot neglect the local scale of historic masonry types. Indeed, traditional construction techniques mostly depended on the local availability of materials, but also on the assimilation of construction practices and their adaptation to the economic resources available for the single building.

3 Methodology

The method of this study is built around the analysis of local contexts, but following a homogeneous approach. The first section of methodology describes the on-site phases carried out in the generic local context, as well as the structure of the dataset, populated by information taken directly on site and indirectly from photographs. Integration of MQI in the dataset is described too. The following section provides criteria and algorithms of the cluster analysis performed on the dataset. The final section shortly describes the case studies where the method was applied.

3.1 Collection and Structure of Data

The method followed in this research (Fig. 1) is focused on local contexts of historic architecture. The local context is intended as an area where materials and construction techniques of historic buildings are homogeneous. It mainly consists of a historic center and the traditional buildings in its neighborhood.

The typological study of local masonry is carried out on the selected local context. Here, photographs are taken of all visible external surfaces of historic masonry structures. Photographs are georeferenced (Fig. 2), to enable the replicability and integration of the study in a subsequent period or by different observers.

Each photograph includes metric references, put in touch with the wall surface. The metric reference allows to scale the photograph properly. Consequently, the photograph is used to verify the geometric measurements taken on site (dimensions of wall units and mortar joints) and to estimate average values of the same dimensions for the portrayed part of masonry. For this purpose, each photograph is captured perpendicular to the wall surface (at constant distance, if possible) or, if this is impeded, the position is chosen to limit perspective effects to the minimum.

The photographic campaign is complemented with inspection and measurement of cross-sections in damaged structures and indoor wall surfaces in accessible buildings, but the analysis is necessarily limited to external masonry surfaces in the great majority of cases.

Table 1. Quantitative variables in the analysis of masonry walls

	Width	Height	Depth	Thickness	Frequency
Masonry unit	min; max; average	min; max; average	Average (if available)	–	–
Horizontal joint	-	–	–	min; max; average	–
Vertical joint	-	–	–	min; max; average	–
Regularization	average	average	–	–	number of elements

Two groups of qualitative data are collected. In the first one, the construction feature is noticed as present or absent: this is the case of filling elements, and elements used for the regularization of horizontal courses.

In the second group, the construction feature is described. This group includes: materials of masonry units, filling elements and regularization elements (the information is the name of material, such as quartz sandstone, conglomerate, argillite, brick); and the shape of masonry units (cut-edge units, roughly cut units, irregular units, mix of irregular and roughly cut units).

A sub-set of both qualitative and quantitative data is specific to the calculation of MQI and considers very important construction features, which otherwise would be represented as qualitative variables (present, absent): presence and frequency of perpends and non-transverse headers, staggered vertical joints, and continuous horizontal courses.

The MQI combines eight parameters, according to the relation $MQI = r \cdot SM \cdot (SD + SS + WC + HJ + VJ + MM)$ [9]. Factor r is used to express the greater importance

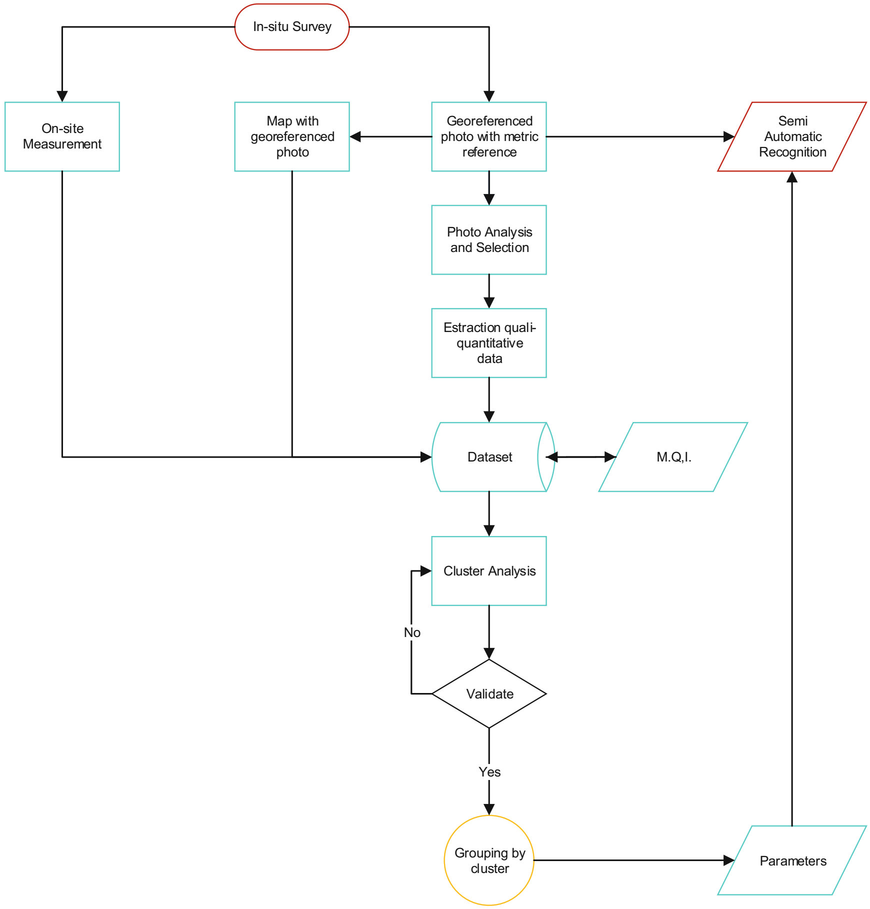

Fig. 1. Flow chart of the method of classification of wall types © 2024, Erica La Placa.

of mortar quality in brickwork masonry compared to stone masonry. In the latter, factor r is equal to 1.

The remaining seven quality parameters are: stone/brick mechanical properties and conservation state (SM), stone/brick dimensions (SD), stone/brick shape (SS), wall leaf connections (WC), horizontality of bed joints (HJ), stagger properties of vertical joints (VJ), and mortar properties (MM). Each quality parameter is expressed by a numerical score. The score indicates if the criteria, which determine masonry quality from the point of view of one parameter, is fulfilled (F), partially fulfilled (PF) or not fulfilled (NF) [13].

Values assigned to the MQI parameters depend on loading conditions. The method considers three conditions, namely vertical static loads, out-of-plane static and dynamic loads, in-plane dynamic loads. Weights between 0 and 3 are given to each parameter according to the loading condition, because this influences the effect of each quality parameter on the overall mechanical quality of the wall. Therefore, three MQI values are calculated for the wall, and each one is referred to one loading condition [13].

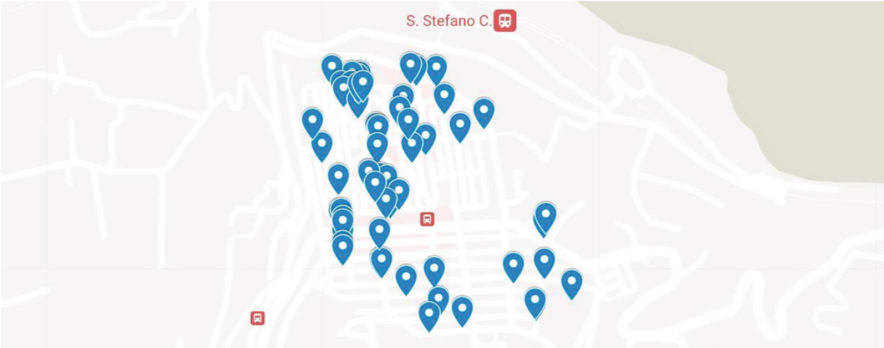

Fig. 2. Georeferentiation of examined masonry walls: example in the case study of Santo Stefano di Camastra © 2023 Aurora Scianò.

The sub-set of MQI data collected for each examined wall consists of: assessment of construction criteria (F, PF, NF) for each quality parameter; weights related to the three loading conditions for each quality parameter; the final values of MQI for the three loading conditions.

A final qualitative variable is included in the dataset for each examined wall. This information is the masonry type, determined through the traditional approach of masonry typology: namely the masonry type which the analyst attributes to the wall, according to the recurrent construction features observed in the local context.

This masonry type is added as a control variable, to be compared with the results of cluster analysis. It is expressed by a code, which is made of three parts. The first part shows the prevalent material of masonry units: SM is used for stone masonry, BM for brick masonry. The second part is numerical and indicates the shape of masonry units, which is relevant for stone walls: 1 is used for cut-edge units, 2 for roughly cut units, 3 for irregular units. These two parts of the code define the essential groups for an intuitive description of masonry types, especially for stone walls. Since local construction features generally require a more refined classification, the code includes a third part. This is used to distinguish masonry types, which are referred to the same group (for instance, SM2.1 and SM2.2 as two stone masonry types, which are both classified in the general group of walls made of roughly cut stones). Figure 3 Shows the images of three types of masonry found in the municipality of Santo Stefano di Camastra.

3.2 Cluster Analysis

Cluster analysis is a statistical method, used to structure the observations into homogeneous groups (clusters), which are characterized by similar values of the analyzed parameters [15]. It allows to examine if a sample of observations can be distinguished in distinct subgroups, based on a set of variables. This method is useful to identify structures within the dataset, thus facilitating the interpretation of data. In this research, cluster analysis is used to structure the qualitative and quantitative information, which was collected for single walls, in masonry types.

Fig. 3. Masonry types of Santo Stefano di Camastra © 2023, Aurora Scianò.

The classification algorithms employed to identify masonry types are non-divisive hierarchical algorithms (Daisy – Pam). Through non-hierarchical methods, cluster analysis is processed until well-structured clusters are determined. For these methods, the cluster structure is assessed through the average silhouette width (ASW). Calculated for each object, this index is the normalized difference between the average dissimilarity with other objects in the same cluster and the average dissimilarity with objects in the nearest different cluster. The overall silhouette index for the entire clustering is the average of the silhouette widths of the objects. The index varies from -1 to 1: the higher the index, the better the clustering, with objects well assigned to clusters based on internal similarities. Negative value of ASW means that the object is more similar to those in other clusters than to the objects in its own cluster. The following ranges of ASW can be considered: if ASW < 0.26, no cluster structure is identified; in the range 0.26–0.50 the structure is weak; in the range 0.51–0.70 the cluster structure is plausible; if ASW > 0.71 the cluster structure is strong [16].

In this study, cluster analysis was carried out using the R software. Three interconnected decisions are required to perform cluster analysis: calculating the distance, selecting a clustering algorithm, and determining the number of clusters.

As described in Sect. 3.1, this study includes continuous, ordinal, and nominal variables. Gower distance (1971), known for its flexibility in handling mixed data, was chosen as the distance metric. Gower distance is appropriate to mixed data clustering because it enables the comprehensive assessment of similarity between observations. Gower distance measures the difference between two records, considering a combination of categorical and quantitative variables. This metric, with a scale ranging from 0 (identical) to 1 (maximally dissimilar), provides a detailed evaluation of differences between observations, accounting for the heterogeneous nature of the variables involved.

Partial dissimilarities between individuals are computed considering the nature of variables involved. Specific metrics are described for quantitative, ordinal, and nominal variables. Given that p is the total number of variables, and $s_j(x_1, x_2)$ is a function calculating the similarity and dissimilarity between the values of the j variables for observations x_1 and x_2, Gower distance D_{Gower} is calculated in Eq. (1):

$$D_{Gower}(x_1, x_2) = 1 - \frac{1}{p} \sum\nolimits_{j=1}^{p} s_j(x_1, x_2) \quad (1)$$

The Partitioning Around Medoids algorithm (PAM) is used for clustering. It employs medoids as representative of clusters and is integrated with Gower distance. The silhouette method is particularly appropriate to identify the ideal number of clusters when PAM algorithm is used. The choice of the number of clusters plays a crucial role in clustering analysis. If the number of clusters is too small, the analysis may result in under-aggregation: data with similar characteristics are excessively grouped together, thus missing significant details. Conversely, too many clusters may result in over-aggregation: data is divided into excessively small groups, and identifying distinct patterns becomes difficult.

The average silhouette width is effective to guide the decision on the number of clusters, by assessing the internal cohesion and separation between clusters. The optimal number of clusters, k, is the number which maximizes the average silhouette over a range of possible values of k.

3.3 Case Studies

The study has been applied to four local contexts in Sicily, namely the historic centers of Castel di Lucio, Patti, Santo Stefano di Camastra, and Tusa. Their architectural heritage is built of stone masonry, with interesting integration of brick in the case of Santo Stefano di Camastra. It was observed that the prevalent masonry material is quartz sandstone, apart from the local context of Santo Stefano di Camastra, which is characterized by the use of sandstone. Geological maps [17] were employed to integrate the observation of lithotypes.

Since the analysis is carried out on visible masonry assessments (not plastered walls, surfaces with disintegrated plaster, or damaged structures), the investigation cannot include all historic buildings in the local context. A total of 157 observations has been collected: 24 in Castel di Lucio, 25 in Patti, 47 in Tusa, 61 in Santo Stefano di Camastra. In the cluster analysis, each examined wall has been treated as an observation.

4 Result and Discussion

Based on the set of data collected for each observation, i.e. for each masonry wall in the four case studies, the cluster analysis has been carried out by using both the qualitative and quantitative variables. About the latter, for the variables for which average, minimum and maximum values were collected (Table 1), only the average values have been considered in clustering. As far as MQI is concerned, the results pertaining to the single observations were used in the cluster analysis, but it is worth reporting the average values calculated for each case study (Table 2).

Table 2. Average M.Q.I. values calculated for each case study

Case study	Average M.Q.I.v	Category	Average M.Q.I. fp	Category	Average M.Q.I. np	Category	Masonry Types
Castel di Lucio	7,37	A	5,75	B	6,19	A	SM2.1
	4,83	B	4	C	4,08	B	SM2.2
Patti	2,63	B	2,47	C	2,42	C	SM2.1
	3,19	B	2,89	C	2,89	C	SM2.2
	2,20	C	1,90	C	2,14	C	SM3.1
	1,90	C	1,55	C	1,95	C	SM3.2
Tusa	7,04	A	5,62	B	6,08	A	SM2.1
	4,77	B	3,81	C	4,20	B	SM2.2
	2,72	B	2,15	C	2,38	C	SM3.1
	1,65	C	1,15	C	1,67	C	SM3.2
S. Stef. di Camastra	6,43	A	5,25	B	4,96	B	SM2.1
	4,75	B	3,67	C	3,87	B	SM2.2

Cluster analysis was carried out both on the single case study and on the entire set of 157 observations. The clustering algorithm was used for various values of k.

For the case study of Castel di Lucio (Fig. 4), an average silhouette width index of 0.27 was obtained, indicating a lack of structure, despite the identification of 4 clusters. This outcome could be influenced by the small number of observations in the considered case study. To achieve better and more homogeneous results, a larger set of observations should be examined.

In the case study of Tusa (Fig. 5), 9 clusters were identified and an average silhouette width index of 0.54 was obtained, suggesting a plausible structure.

For the case study of Santo Stefano, a weak structure with an index of 0.47 was obtained. Nonetheless, as shown in the graph (Fig. 6), cluster 1 is the most populated, and its observations are characterized by silhouette width values greater than 0.47, thus indicating a plausible structure.

Finally, for the case study of Patti (Fig. 7), 7 clusters were identified, with an average silhouette width index of 0.53 d, which indicates a plausible structure. Clusters 1, 3, and 4 have the highest number of observations.

Furthermore, regarding the analysis of the overall dataset, Fig. 8 illustrates three homogeneous groups, with an average silhouette width of 0.46 indicating a weak structure. Cluster 1 mainly includes the observations collected in the case study of Santo Stefano di Camastra (60 observations) and a limited number from Castel di Lucio (3). In cluster 2, 25 observations pertain to the case study of Patti, 4 to Castel di Lucio and 1 to Santo Stefano di Camastra. Finally, cluster 3 is made of 17 observations from Castel di

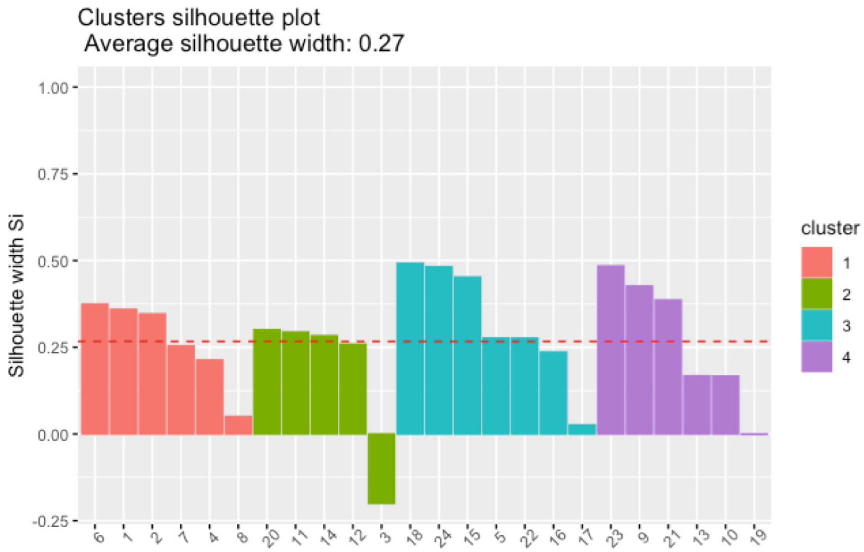

Fig. 4. Cluster analysis dataset Castel di Lucio ©2023, by authors.

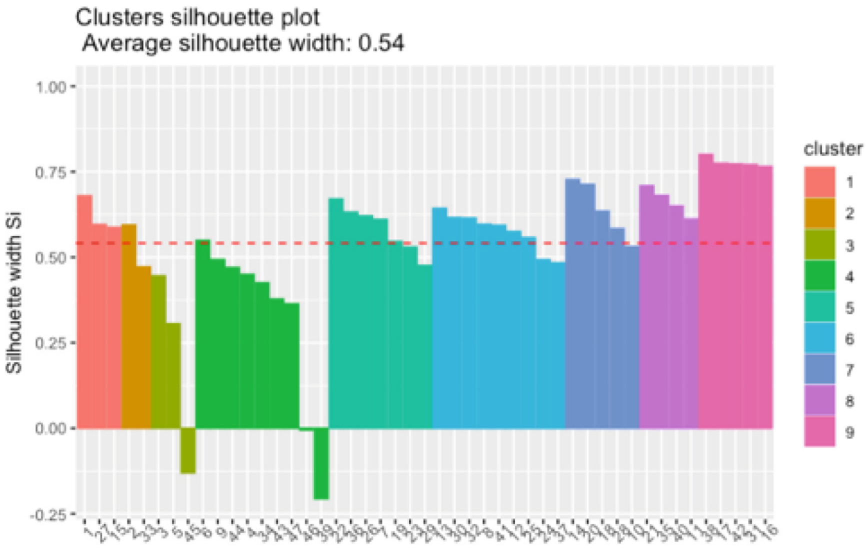

Fig. 5. Cluster analysis dataset Tusa © 2023, by authors.

Lucio and 47 observations from Tusa. Furthermore, all masonry walls made of sandstone belong to cluster 1, while those built with quartz sandstone are divided between clusters 2 and 3.

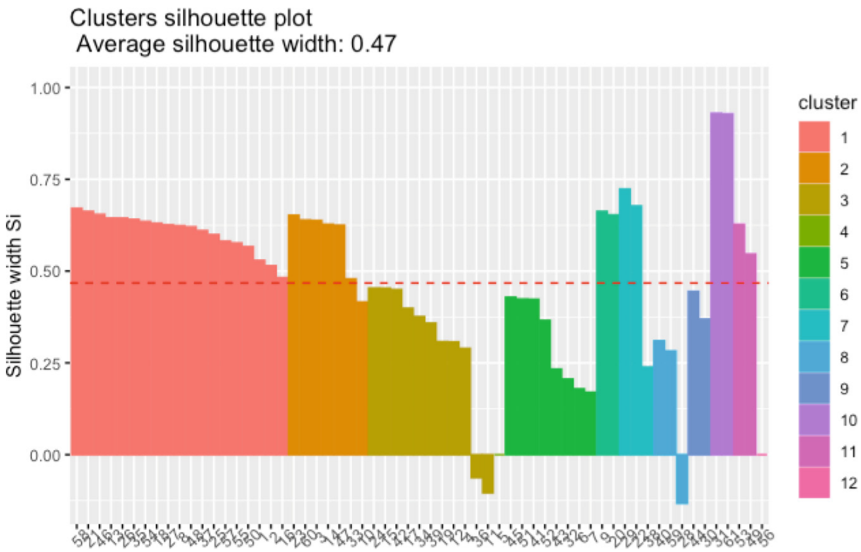

Fig. 6. Cluster analysis dataset Santo Stefano © 2023, by authors.

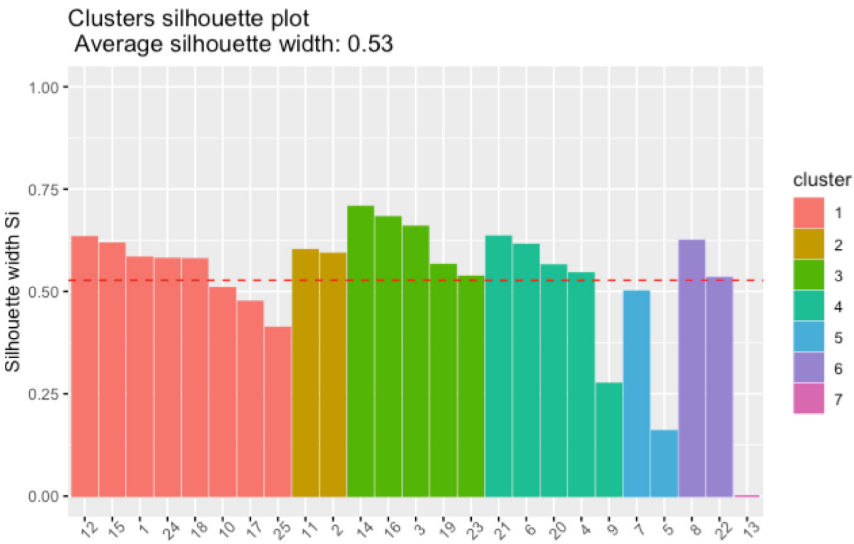

Fig. 7. Cluster analysis dataset Patti © 2023, by authors.

The variability of MQI within each cluster was also examined. In its three values (vertical, out of plane, in the plane), the index is higher in clusters 1 and 3, thus suggesting that masonry walls belonging to these groups have higher mechanical quality (therefore, higher mechanical performances) if compared to walls in cluster 2. The results of this focus on MQI is illustrated by Fig. 9.

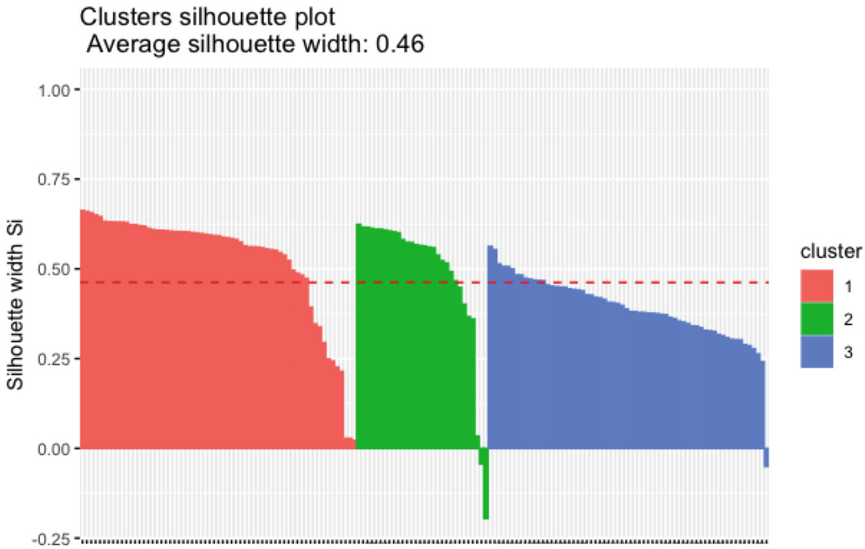

Fig. 8. Cluster analysis of overall dataset © 2023, by authors.

Finally, geometric data associated with the three clusters identified for the entire set of 157 observations (height and width of masonry unit, thickness of horizontal and vertical mortar joint) were analyzed, as shown in Fig. 10. Height of masonry unit is similar in clusters 1 and 3, with higher average value than in cluster 2. Average width of masonry unit is the largest in cluster 1 and the smallest in cluster 2, while the value pertaining to cluster 3 is intermediate. Average thickness of mortar joints is similar in clusters 1 and 3, where it is higher than in cluster 2.

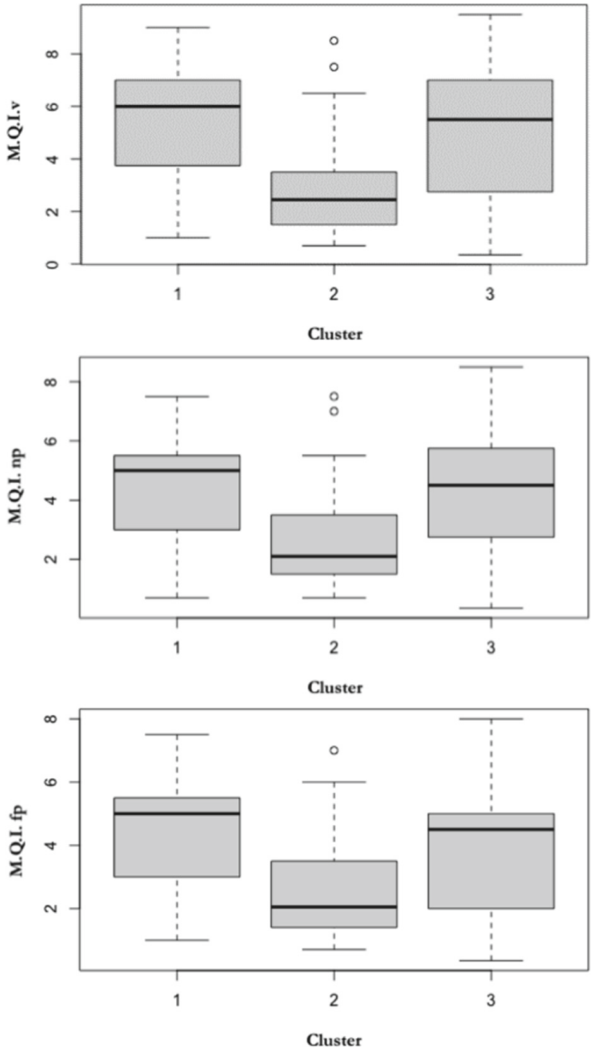

Fig. 9. Boxplots of M.Q.I. within the 3 clusters © 2024, by authors.

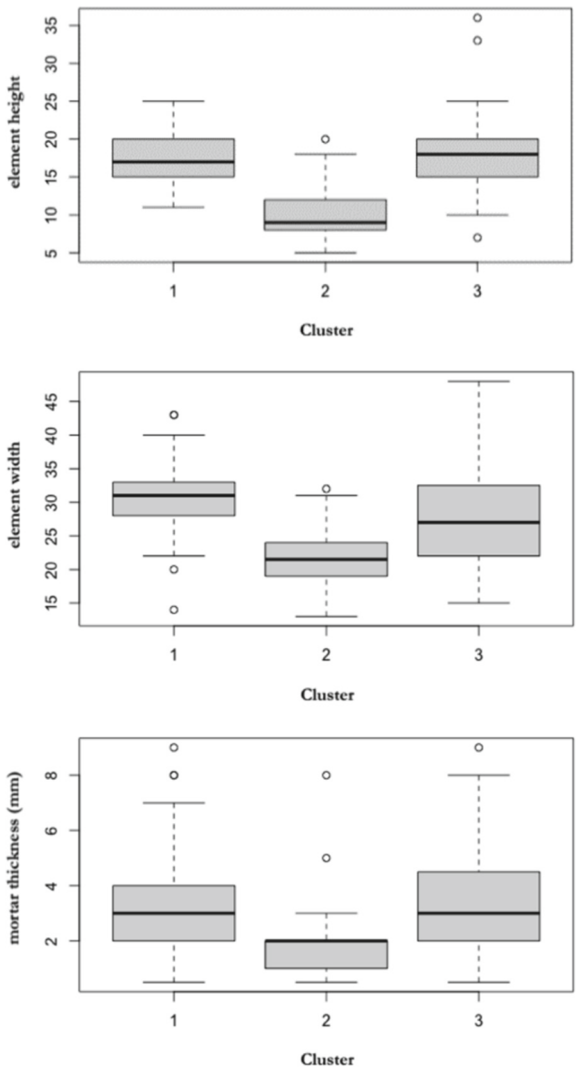

Fig. 10. Boxplots of geometric dimensions within the 3 clusters (a) element height (b) element width (c) mortar thickness © 2024, by authors.

5 Conclusion

The results exposed in this study show that integration of cluster analysis in the methodology of local masonry typology provides a classification, which is appropriate to express the construction features of masonry. Through the cluster analysis, aggregations can be derived for similar variables and, consequently, their probability distribution in homogeneous groups (the clusters) can be examined.

The structure of the dataset proposed in this study, made of up to 54 qualitative and quantitative variables, proved to be applicable to different case studies and to take into account local construction peculiarities. This is the case of Santo Stefano di Camastra. It is characterized by the interesting use of brick fragments on the external thickness of masonry mortars, which are schematized as filling elements in the dataset. The versatility of data structure was confirmed in all case studies, thus suggesting that the proposed set of variables is applicable in general.

On the other hand, the collection of data is necessarily based on the subjective skills of the observer, for instance in the repetitive measurement of geometric, quantitative variables (dimensions of masonry units and mortar joints) on rectified photographs. Therefore, cluster analysis increases objectivity in the identification of masonry types, but the process remains partially influenced by skills and knowledge of the observer.

Consequently, the further development of this research, aimed to improve the proposed clustering method for masonry typology, will consist in the use of deep learning techniques to automate the process of recognition and analysis of masonry walls through photographic images.

Authors Contribution. Conceptualization: E.G., E.L.P. and C.V.; methodology: E.G.; computation: E.L.P.; data curation M.V.; validation M.V.; writing-original draft preparation: E.L.P.; writing-review: E.G.; supervision: R.C. and C.V.

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