A Density-Based Spatial Cluster Analysis Supporting the Building Stock Analysis in Historical Towns

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Abstract

The paper presents the application of a spatial cluster approach supporting the building-stock analysis of historic towns. This method was applied in the town of Calavino, within the Municipality of Madruzzo, an historic settlement located in the Province of Trento and characterized by high natural and heritage values. The proposed data mining approach shows as several buildings can not be classified in clusters for the historic centre of Calavino when physical features are combined with other variables (e.g. building function, owner, age class, shape and physical features, heritage values and conservation state, etc.). After this analysis, detailed energy audits and dynamic simulations can be addressed on specific “*building typologies*”.

Introduction

The conservation of urban heritage is based on the idea of an “*integrated conservation*” as a continuous and complete activity that considers protection, restoration, maintenance, and enhancement of architectural heritage [Council of Europe, 2000; UNESCO, 1976]. This “*trans-disciplinary*” approach endorses planning processes, conservation of cultural heritage (CH), architectonic design, building physics, environmental engineering, community engagement, training, and education [Ginzarlya et al., 2018], in order to consider and to respect the plurality and the diversity of the historic city centres and their capacity to change over the time [UNESCO, 2011]. Besides, the improvement of energy efficiency in building and urban sectors assumed a strategic role for the decarbonization of the EU Countries [European Commission, 2008; European Parliament, 2010 and 2012; European Union, 2009] as well as for the CH conservation. Particularly, the EU Directives [European Parliament, 2010 and 2012] showed the big potential related to the achievement of energy savings and dioxide (CO₂) emissions reduction through the refurbishment of existing buildings, besides the construction of new low-energy ones. Particularly, the intervention on historical buildings and towns is necessary to improve energy efficiency and sustainability. In general, the legislation on CH does not consider energy efficiency [MiBACT, 2004] but, on the contrary, the legislation on energy efficiency considers also the intervention on existing and historic buildings [PdR, 2013]. This concept can be extended also

to historical ensembles and towns [MiBACT, 2004]. Particularly, the improvement of their energy performances plays a strategic role in promoting their regeneration [Roberti et al., 2015]. This operation requires a very detailed knowledge of the existing building stock. On this purposes, the building stock analysis approaches allow a detailed study on the energy performance of an urban area. The most used methodology is based on the “*typology approach*” defined within the International Energy Europe (IEE) projects Tabula [Ballarini et al., 2014], Episcopo [IEE Program, 2013a] and RePublic_ZEB [IEE Program, 2013b]. These projects introduced the criteria for defining a set of “*reference buildings*” representative of the EU housing stocks. This approach focused only on residential buildings, which are characterized by homogeneous features in terms of thermal zone, indoor air temperatures, internal loads and occupancy time. Consequently, the variables adopted were: (i) “*building age class*” that affects the construction features and reflects the changes of the building over the time; and (ii) “*building size class*” that influences the heat losses through the thermal envelope and the surface-to-volume ratio (S/V) [Exner et al., 2017]. Only one age class was identified for historical constructions, considering building built before 1945 without any difference (e.g. pre-industrial or industrial buildings) [Ballarini et al., 2014; IEE Program, 2013a]. This qualitative approach was modified to evaluate the energy performances of historical city centres, in order to contemplate different functions, age classes, and historic values [Lucchi et al., 2018]. As matter of fact, the presence of other functions than residential leads to inhomogeneous thermal zones, and occupancy times. Similarly, the presence of different construction periods and protection levels has an impact on the technological and constructive features and, consequently, on the thermal performance of the building envelope. Thus, the application of simple analogies with coeval buildings in the evaluation of historic towns can causes a series of errors and uncertainties. Possible uncertainty are due to differences in the same building or in the same “*building typology*” [Nardi et. al, 2018], such as: (i) wrong information on construction periods; (ii) specific geometrical or technological features neglected by these methodologies; (iii) different wall textures and thicknesses; (iv) presence of damage and moisture; and (v) ignorance of previously refurbishments. In addition, in alpine areas, the occupancy level of the buildings has an

impact on their energy performance [Lucchi et al., 2018]. A more accurate identification of the representative “building typologies” could improve the results of the energy performance evaluation [Exner et al., 2017]. Due to the complexity of CH, structures and associations in data are hard to find manually and data mining or machine learning approaches are needed. The identification of “building typologies” can be improved with the use of clustering algorithms. These algorithms should consider the presence of noise, i.e. outliers that don’t belong to specific groups or clusters. After this analysis, detailed energy audits and dynamic simulations can be addressed on specific “building typologies”.

Aims

The paper presents a methodology based on the use of data-mining methods, i.e. an hdbscan algorithm, and Geographic Information Systems (GIS) integration, to overcome the inaccuracies related to the application of the traditional building stock analysis approach in a historic town. Buildings are classified according to their features, considering the most important parameters for the energy assessment of a historic town, such as building function, owner, age class, shape and physical features, heritage values and conservation state (Table 1). In fact, consistently defining “building typologies” is crucial in order to evaluate the energy demand and to support the building stock analysis and the energy simulation of towns or districts. The method was applied to the historic settlement of Calavino, an old town located in the alpine space area of Italy (Province of Trento). Starting from this study, technicians can evaluate the energy performance of historic towns, as well as define clear rules for renovation measures and for the development of energy policies.

Methodology

Following the steps described in [Fayyad et.al, 1996], the research method was structured in the following phases: (i) data collection and selection, based on on-site survey and GIS analysis; (ii) data processing and transformation; (iii) data mining for identifying patterns and structures in the selected data-set; and (iv) interpretation and evaluation of identified patterns by means of GIS and statistics analysis.

In the case of cluster analysis, the data collection and selection is a crucial step. All the selected variables contribute to define the cluster structure. The use of not relevant data can hide the useful information provided by other [Kaufman and Rousseeuw, 1990]. Data selection was based on the following techniques: (i) historical analysis (HA); (ii) on-site surveys; (iii) photographic campaigns; (iv) qualitative infrared thermography (IRT) surveys; (v) analysis of the Energy Performance Certificates (EPCs); and (vi) GIS analysis. From these assortments, a specific datasheet was produced for each building. Several on-site visits and IRT surveys permitted to identify: (i) building use; (ii) building owner; (iii) building age class; and (iv) building shape and physical features. Otherwise, heritage value and conservation state

were evaluated by HA and on-site surveys. First, considering the heritage constraints and values, the parameter on building owner was divided into (i) public, (ii) private, and (iii) body governed by public law. Second, considering the results of historical researches and maps, the parameter on building age classes was divided into: (i) ante-1860, (ii) between 1860 and 1939, and (iii) post-1939. Finally, considering the architectonic dimensions and features of the building stock, the parameter on building shape and physical features was divided in (i) detached, (ii) agglomerate, and (iii) linear. Dimensions and data sources are reported below (Table 1).

Table 1: Dimension and source of data used for each selected variable.

Dimension	Sources of data	Selected variables	Kind of variables
Building functions	On-site survey, photog. campaign	BF	Categorical
		Use _{gr} , Use _{other} , Use _{attic}	Categorical (-, used, underused, not used)
	IRT survey	n _f , % _{use}	Continuous
Building owner	On-site survey	Owner	Categorical (public, private)
	Building regulations	Heritage constraints (CH)	Categorical (-, yes, no)
Building age classes	Statistic data	BA	Number
	HA (CH records)		
	HA (books, CH records)	Different ages	not available (n.a.)
		History of the building	n.a.
Building shape And features	HA (original designs, books)	A, n _f , hf, H _{mean}	Continuous
	GIS analysis	S/V, H _{min} , H _{max}	Continuous

	On-site survey, photographic campaign	BT	Categorical (aggregated, detached, linear)
	HA (original designs, architectonic repository)	T _{glass} , T _{win} , T _{wall} , T _{roofst} , T _{roofcover} , T _{roofshape}	Categorical with description
	National standards	Thermal properties of the building envelope (opaque envelope and windows)	n.a.
	IRT survey		n.a.
	EPCs Analysis		n.a.
	HFM		n.a.
	Energy data analysis	Data on hot water supply	n.a.
	EPCs Analysis	Thermal zones	n.a.
	EPCs Analysis	Data on renewable energy sources	n.a.
	Energy data analysis		n.a.
Heritage values	HA (CH records, building regulations)	Building constraints	n.a.
Conservation state	HA (CH records)	Conservation	Categorical (low, medium, high)
	HA (CH records)	Moisture and surface decay	n.a.
	IRT survey		n.a.

Some of these variables are categorical, e.g. material and construction methods. Each category value has been converted into a new variable and set the value 1 or 0. This

has the benefit of not weighting a value improperly. On the other hand, the dimensionality of the space is increasing. All the variables are standardized and to each group of categorical variables has been assigned the same weight.

The use of a density-based spatial cluster [Campello et al. 2013] allows identifying “*building typologies*” by grouping together building that are *close* to each other. Especially, the hdbscan algorithm marks as outliers the buildings in low-density region. This is done by introducing a different metric called mutual reachability distance. The cluster analysis has been performed on different subsets of selected variables in order to better understand how the high-density region and the outliers change by introducing new variables describing buildings. Finally, the use of GIS tools allows to graphically visualizing on the cartography the spatial distribution of “*building typologies*” and their potential for the energy renovation of historical towns.

Results and discussion

The methodology has been applied to the municipality of Calavino in the Province of Trento. Calavino lies at an altitude of about 400 m a.s.l. in the Valle dei Laghi and has a cold and dry climate. The town is formed by 220 constructions that corresponds to a total covered area of around 22,840 m². It has a compact morphology, with aggregated buildings to shelter from cold weather conditions (e.g. prevailing winds, rain, and sun). The original town stretched around an ancient road of the XVIth century. Along the street, on both sides, the houses were built as traditional buildings lined up continuously. Materials used were natural stone (masonries, foundations, portals and roofs), wood (ceilings and window frames), and straw mortar (internal part of ceilings). Next to this area, several dedicated buildings (i.e. the theatre and the school) were built in the early decades of the XXth Century. Materials used in this case were solid, alveolar bricks, cement (masonries, ceilings), and wood (ceilings of rural buildings and window frames).

Spatial cluster analysis

All the information about the historic town were geo-referenced and spatially linked to each building footprint using an open-source software (i.e. GRASS GIS and QGIS), to considered the spatial distribution of energy demand and supply patterns from a geographical point of view. A table was created that contains all the information collected (by developing a macro in Excel) and it was connected with the shapefile inside the GIS software, using the ID number of each building. In this way, several maps were created with different data and combinations of them. They concern: (i) heritage value and conservation level; (ii) utilization level; (iii) architectonic features of the building envelope (both for the opaque and the transparent part); (iv) distribution of solar thermal and photovoltaic systems; (v) energy rating levels of the

building units documented by the EPCs; and (vi) reference building typology. The composition of the building stock is shown below (Table 2).

Table 2: Composition of the building stock.

Building functions			
Residential use	Special use	Auxiliary use	Other use
79.4 %	8.6 %	11.5 %	0.5 %
Building owner			
Public	Private	Body governed by public law	
4.8 %	90.9 %	4.3 %	
Building age classes			
< 1860	1860-1939	> 1939	-
84.2 %	3.8 %	12.0 %	-
Building shape and features			
Detached	Agglomerate	Linear	-
15.8 %	42.1 %	41.6 %	-
Heritage value			
Listed building	Protected building as historic ensembles	Not listed building	
		Without CH value	With CH value
5.8 %	1.9 %	75.1 %	17.2 %
Conservation state			
Low	Medium	High	No info
56%	26.8%	13.9%	3.3%

The GIS analysis showed the presence of some buildings abandoned (9.1%) or almost abandoned (2.4%). Only about half of them are entirely used (51.7%), while in 26.3% the attic floor is not used and in 9.1% one or more floors are not used. The following map gives an overview of the utilization level of the analysed buildings (Figure 1).

Figure 1: Utilization level of the historical building stock (Source of data: Municipality of Madruzzo, own elaboration, Bing maps).

Similarly, the IRT survey revealed the presence of several partially heated and not heated buildings (Figure 2).

Figure 2: Examples of the IRT survey of the building stock (Source: own elaboration).

In parallel, the cluster analysis allowed to better analyse the specificity of buildings and to identify patterns in the dataset. Only private buildings were clustered (Figure 3).

Figure 3: Reference building typologies (Source of data: Municipality of Madruzzo, own elaboration, Bing maps).

Figure 4 reports the results of the cluster analysis by considering only the building shapes.

Figure 4: Clusters with building shape and physical features, data projected into two dimensions via t-sne.

Only 8 outliers were identified by the cluster algorithm. This means that the physical parameters allow to identify mainly 3 clusters: (i) Cluster 0 with buildings with greater floor surface, mainly 3 floors and detached; (ii) Cluster 1 with higher buildings, mainly 4 floors, and linear; and (iii) Cluster 2, with higher buildings, mainly 4 floors, and aggregated. In Figure 5, the mutual reachability distance among buildings is shown. Clusters 1 and 2 have closer features while more detached buildings belong to Cluster 0, as shown in Figure 6. Detached buildings are usually located in the peripheral area.

Figure 5: Clusters of building shapes and physical features, mutual reachability distance.

Figure 6: Clusters of building shapes and physical features (Source of data: own elaboration, Bing maps).

The number of clusters increases if only variables related to building uses and functions are considered. Besides, the number of outliers, 16 buildings in Cluster -1, become relevant (Figure 7). This means that in CH, the function of the building becomes crucial to identify building typologies. The Cluster 0 represents the forsaken buildings. In Cluster 1 the heated percentage is quite low and all the floors are underused. Buildings in Cluster 2 have all the floors used. In Clusters 3 and 4 the information about the use of the attic is mainly missing, but in Cluster 3 the number of heated floors is higher. The attic is underused in Clusters 5, 6 and 7, while the heated percentage changes. In Cluster 7 the number of heated floors is equal to three.

Figure 7: Clusters of building features, data projected into two dimensions via t-sne.

If variables related to building shapes and physical features are combined with the degree of utilization, the number of outliers increases to 82 (Figure 9). The mutual reachability distance of these outliers (Figure 10) is quite high and the peculiarity of these buildings does not allow to group them in a cluster with similar features. Consequently, for them it is not possible to identify a representative typology. Notice that all the detached buildings cannot be grouped in a cluster and they are mainly outliers. Figure 8 highlights the differences of some selected features for the detached buildings. Thus, for them is important to consider specific features (i.e. area, number of floors, conservation level, use), not only the traditional parameters considered in the “building typology approach” (i.e. age, physical features).

A	n_i	S/V	H_{heated}	t_{win}	t_{wall}	CH	Conservation	Use _{gr}	Use _{attics}	Use _{attic}
56	4	0.5	9	single	stone	Yes	low	used	used	-
60	3	0.8	10	single	stone	No	high	-	-	-
67	3	0.8	6	double	stone	No	low	-	-	-
76	3	0.7	12	single	stone	-	high	-	-	-
88	3	0.6	7	double	mixed	-	low	-	-	-
92	5	0.5	12	double	mixed	-	low	-	-	-
101	2.5	0.6	10	single	mixed	-	medium	used	used	underused
114	4	0.5	8	single	stone	-	low	used	used	underused
128	4	0.7	10	double	mixed	-	low	-	-	-
134	3	0.6	7	single	stone	-	medium	underused	used	underused
144	4	0.4	10	single	mixed	-	medium	-	-	-
147	3	0.5	11	single	stone	No	low	-	-	-
159	5	0.4	12	double	stone	No	low	-	-	-
161	4	0.5	10	single	stone	-	medium	-	-	-
164	3	0.5	11	double	mixed	-	low	-	-	-
172	3	0.4	7	double	stone	-	low	used	used	underused
222	4	0.4	10	single	stone	Yes	medium	underused	underused	underused
263	4	0.4	13	double	stone	No	medium	used	used	not used

Figure 8: Heat map of selected features for detached buildings

Figure 9: Clusters of building shape and physical features with building functions, data projected into two dimensions via t-sne.

Figure 10: Clusters of building shape and physical features with building functions, data projected into two dimensions via t-sne.

features with building functions, mutual reachability distance.

The resulted clusters are the following.

- Cluster 0: four buildings with mainly a medium-high degree of conservation, roof with 1-2 pitches, stone wall. Not in all the buildings there is a double glazing even if these buildings have the higher conservation status. In these buildings only the first floor is used.
- Cluster 1: 21 buildings with mainly the following features: stone wall, not heritage constraints, linear elements. The degree of utilization is mainly unknown.
- Cluster 2: four buildings with a very low degree of conservation but a good degree of utilization. They are mainly pavilion, the wall is done by mixed material. They are mainly aggregated buildings.
- Cluster 3: 45 buildings with double glazing, stone wall, linear elements, and medium-low degree of conservation. The attic is under used while the other floors are generally used.

In Figure 11, the clusters are spatially represented. Notice that there is no a spatial closeness among buildings with similar features. Buildings of Cluster 2, the green cluster in Figure 11 (low level of conservation but good level of utilization), are mainly in the centre of CH and they are spatially closed. All the buildings classified as -1, dark grey in Figure 11, are outliers.

In conclusion, introducing an hbscan algorithm allowed to better understand the features of the dataset and not to force buildings to be classified in a group. By considering only the shape and the physical feature of the buildings, the dataset is grouped in 3 defined classes. If other parameters, such as building utilization level, heritage constraints and conservation degree are considered, the dataset shows a higher number of outliers. This means that the peculiarity of a CH does not allow a clear classification of the buildings in groups and there is not a strong relation among building shapes, features and use of the buildings.

Figure 11: Clusters of building shape, physical features and building functions (Source of data: own elaboration, Bing maps).

Conclusion

This paper has shown how to apply a spatial clustering analysis, using hdbscan algorithm, to identify the reference building typologies of an historic building stock. The analysed variables were: (i) building features and typologies; (ii) building ages; (iii) historic values and conservation states; (iv) technological aspects; (v) building use. First, building features and typologies have an important role in the definition of clusters for this type of towns. By considering only the building shape and physical features, as normally used in the “*typology approach*” [Ballarini et al., 2014; IEE Program, 2013a; IEE Program, 2013b], the number of outliers is quite low. The dataset has a tendency to clusterize. This means that the “*typology approach*” can be used also in historical towns if we consider only the physical features. On the contrary, building age is not a relevant data for the definition of cluster in this historical towns. As matter of fact, the available archival and historical sources do not allow the precise distinction of the ages of structures built before 1880. In fact, historical buildings data mainly come from cartographic maps and documents, that give a precise characterization of building built from 1880 and 1945. On the contrary, historic buildings data derive from archival documents and books and, thus, are more precise.

Historic values and conservation states are crucial variables in CH. Information on technological aspects are mainly categorical and they can strongly influence the results of the cluster analysis. However, adding building use information to historical values and technological aspects becomes really important for the cluster definition. In fact, the number of outliers becomes relevant. Next step of this work will be the identification of parameters that can influence the evaluation of energy demand according to the building stock. Considering the peculiarity of CH is crucial in order not to overestimate the energy needs.

Acknowledgement

This research work was financed by the Municipality of Madruzzo. We tank to Michele Bortoli, the Mayor, and the technicians of the Municipality. Also, an acknowledgement is given to Susanna Serafini and Maria Stella Marini for collecting the data on the historical building stock.

Nomenclature

CH	Cultural Heritage
EU	European Union
CO ₂	Greenhouse gas
RES	Renewable energy sources
SEAP	Sustainable Energy Action Plan
IRT	Infrared Thermography
IEE	International Energy Europe
Tabula	Typology approach for building-stock energy assessment
Episcope	Energy performance indicator tracking

	schemes for the continuous optimization of refurbishment processes in European housing stocks
RePublic_ZEB	Refurbishment of the Public Building Stock Towards nZEB
HVAC	Heating, ventilation and air-conditioning
S/V	Surface-to-volume ratio
HA	Historical analysis
GIS	Geographical Information System
EPCs	Energy Performance Certificates
HFM	Heat Flux Meter
A	Area
n _f	Number of heated floors
h _f	Floor height
H _{mean}	Mean high
H _{min}	Minimum high
H _{max}	Maximum high
Use _{gr}	Utilization level of ground floor
Use _{other}	Utilization level of other floors
Use _{attic}	Utilization level of attic
% _{use}	Percentage of utilization
BA	Building age
BT	Building typology
T _{glass}	Materials and construction methods of window glass
T _{win}	Materials and construction methods of windows
T _{wall}	Materials and construction methods of walls
T _{roofst}	Materials and construction methods of roof structure
T _{roof cover}	Materials and construction methods of roof cover
T _{roof shape}	Materials and construction methods of roof shape

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