

Definition of building archetypes for the Italian Alpine areas

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Abstract. Recent research on building performance simulation showed the need for building archetypes in order to reduce the computational load and facilitate the generalization of the results, considering not only the analysis of the current energy performance but also the impact of different refurbishment strategies as well as of climate scenarios. Despite the significant role played by building archetypes, there is a general lack of detailed information describing national building stocks – an issue which is even more critical for the mountain areas, characterized by low urban density and fewer possibilities to collect building data. In this framework, this paper presents a set of residential building archetypes for the Italian North-Eastern Alpine region, identified by combining different statistical techniques and through the use of datasets of shape, size, and structure of buildings, as well as data on simulated energy performance in both typical and extreme climate conditions in four representative locations. The results obtained can be used for future applications to identify necessary adaptations and improvements to enhance the sustainability and resilience of Alpine residential buildings.

Keywords: Building archetypes, mountain regions, key input parameters, typical and extreme climatic scenarios

1 Introduction

The peculiar environmental and socio-economic characteristics of the European mountain regions lead to several challenges in the implementation of decarbonization strategies for the local building stock and in the achievement of the energy efficiency targets set by the Energy Performance of Buildings Directives [1, 2]. Indeed, detailed information describing the building stock is often limited [3, 4], and such issue of data scarcity is particularly pronounced when it comes to the mountain

regions. As a consequence, the combination of low urban density and almost negligible building data accessibility [5] make it difficult to identify representative building archetypes for these areas. In this context, the analysis presented in this work aims to address these gaps by developing a comprehensive set of residential building archetypes tailored to the characteristics of northern Italy mountain regions, with the potential for extension and application to neighboring countries with similar climatic and building conditions. To achieve this goal, the existing building stock was studied to define a set of ten representative archetypes and simulate their energy performance at single building scale, accounting for multiple Alpine typical and extreme climatic conditions.

2 Case study analysis and energy simulations

2.1 Definition of the input parameters

Research work was conducted implementing complementary approaches. On one hand, available geometric data were analyzed to find regional representative building dimensions and orographic context conditions; on the other hand, a literature review was performed to characterize the building envelope typologies of the Alpine existing building stock.

2.2 Geometry and context features

Seven geometrical metrics (among those represented in Fig.1) were computed for all buildings located in the Italian climate zone F of the two Autonomous Provinces of Trento and Bolzano/Bozen – South Tyrol (i.e., all municipalities with Heating Degree-Days calculated with respect to a base temperature of 20 °C, HDD_{20} , larger than 3000 K d), which represents the most common climate zone in the Alpine region. This task was performed by using Geographic Information Systems (GIS) and the studied metrics included (1) building footprint area, (2) volume, (3) surface-to-volume ratio (S/V), (4) elongation, (5) shape factor, and (6) edge ratio, (7) sky view factor (SVF). These metrics enabled the definition of equivalent buildings, following the procedure proposed by Battini *et al.* [6]. As a whole, almost 190'000 building geometries were analyzed.

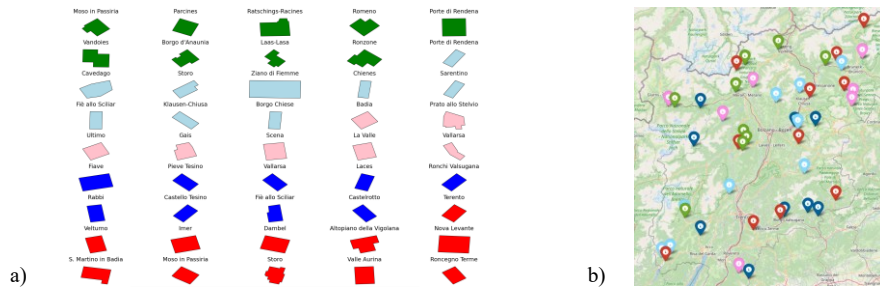


Fig. 1. Geometry (a) and geographical location (b) of selected buildings. Light blue color indicates the buildings close to the 10th percentile, dark blue to Q_1 , dark red to the median, light red to Q_3 , and green to the 90th percentile

To ensure the geometric representativeness of the equivalent buildings, their dimensions were compared with those of significant cases extracted from the empirical distribution of the dataset of real buildings. Specifically, 10th percentile, first quartile (Q_1), median, third quartile (Q_3), and 90th percentile of the equivalent building distribution were taken as reference values for this comparison.

The most representative building geometry was then selected for each of these percentiles based on the smallest absolute deviation from the reference values, with a maximum difference of 0.5 m for the extreme percentiles (10th and 90th) and 0.3 m for the intermediate values (Q_1 , median, and Q_3). This selection process resulted in four distinct representative building cases, whose geometrical properties are summarized in Table 1. The 10th percentile was excluded from the final analysis because its overall footprint area was too small (i.e., about 55 m²) and thus considered not in agreement with the scope of the analysis. In order to include the influence of the surrounding orographic context in the definition of the building archetypes, the Sky View Factor (SVF) was selected as an additional seventh metric. SVF values were computed for each real building in the dataset using Relief Visualization Toolbox (RVT) [7]. This time, only Q_1 , median, and Q_3 values were retained for further analysis, excluding the context for isolated groups of buildings in the narrowest valleys or on top of the mountains.

Finally, given the absence of a clear prevailing building orientation within the study region, two main orientations were considered for each case, respectively North-South (N-S) and East-West (E-W), resulting in 24 potential combinations. However, the change of orientation was not applied to the 90th percentile case, which exhibits a nearly square footprint; for this reason, only 23 cases were considered.

Table 1. Properties of the selected building archetypes: a) Geometry, b) Sky View Factor and c) Orientation

a) GEOMETRY					Area	Number of
		x [m]	y [m]	z [m]	[m ²]	Floors [-]
1	Q ₁	13.5	8.0	5.8	108	2.0
2	Median	15.5	11.5	7.9	178	2.5
3	Q ₃	17.5	15.5	9.0	271	3.0
4	90 th percentile	22.0	21.0	9.6	462	3.0

b) SKY VIEW		SVF
FACTOR		
1	Q ₁	0.61
2	Median	0.75
3	Q ₃	0.87

c) ORIENTATION	Description
1	Longest side: N-S
2	Longest side: E-W

2.3 Building envelope features

During the first phase of the literature review, several publications on Alpine architecture were revised to check for relevant information about the building techniques and materials typically used in this region. Most of the reviewed documentation addresses the subject from an architectural design point of view, including extensive analysis on the morphological solutions and only few data about the geographic diffusion of the described construction techniques. Selection of relevant materials and envelope components was completed with a throughout revision of regional building standards, gathering information concerning thermal transmittance within specific areas of diffusion [8].

Finally, the building stock was grouped in five different construction periods, according to the similarities found among the buildings' properties: 1900-1949, 1950-1969, 1970-1989, 1990-2014 and after 2015. In the analyzed building stock, the thermal transmittance of glazed surfaces ranges between 1.5 and 2.7 W/(m² K), since the percentage of single glazed windows is currently negligible in the considered area. Roof and floor structures are made of either reinforced concrete or timber; roof stratigraphy varies from 0.2 to 2.5 W/(m² K), while slab structures range between 0.28 and 2 W/(m² K); the lower transmittance values correspond to more recent buildings, reflecting improvements in construction standards and insulation technologies. Additionally, two different typologies of opaque vertical walls were considered for each time period - high and low thermal capacity walls, based on the calculated thermal capacity for the building envelope components. Table 2 shows the main envelope structures defined for the vertical elements as an example.

Table 2. Characteristics of the selected walls by construction categories and periods

Period of construction	Type	Thickness [cm]	U-value [W/(m ² K)]	Thermal capacity [kJ/(m ² K)]
High thermal mass				
1900-1949	Stone and mortar masonry with exterior plastering	82	1.86	1877
1950-1969	Stone and mortar masonry with interior wood cladding	92	1.03	1920
1970-1989	Hollow core brick masonry	39	0.67	378
1990-2014	Concrete masonry cast-in-place	34	0.34	308
after 2015	Concrete masonry cast-in-place with insulation	44	0.28	880
Low thermal mass				
1900-1949	Solid brick masonry	16	2.58	280
1950-1969	Semi-solid brick masonry	29	1.18	314

1970-1989	Solid brick masonry with cavity	41	0.60	579
1990-2014	Hollow core brick masonry	34	0.34	394
after 2015	Framed wall with solid wood mullions and external insulation	27	0.20	250

2.4 Simulation settings

Based on the combination of geometry, context, and building envelope features, 210 configurations were defined. EnergyPlus simulations were carried out to calculate hourly and annual energy demands for space heating of each building, considering four different locations within the study area well spread in the region and with different HDD_{20} : Brunico-Bruneck, Curon-Venosta, Moena, and Pergine Valsugana.

Infiltration rates of 0.5 h^{-1} and internal gains 4 W/m^2 were considered; occupancy profiles for residential buildings were based on the standard EN 16798-1 [9]. Each simulation considered two different climate scenarios developed from the ERA5-Land hourly data series of dry bulb temperature, relative humidity, and global horizontal irradiance of the period 2008–2022: (i) a weather file representing a typical year and (ii) a weather file reflecting extreme conditions [10]. Finally, as regards the modelling of the surrounding orographic context, a simplified box with dimensions of $300 \text{ m} \times 300 \text{ m}$ was modelled to represent the impact of the environmental context. The height of the box was adjusted to match the representative SVF values and to ensure a realistic approximation of the surrounding context.

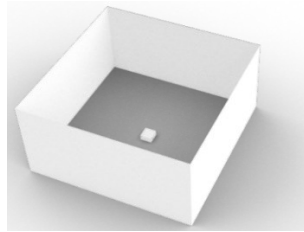


Fig. 2. Simplified 3D model of the surrounding orographic context

2.5 Example of energy simulation results

From EnergyPlus hourly energy needs for space heating, the corresponding monthly and annual values were calculated for each building configuration. As an example, Figure 3 shows the specific monthly heating needs for the different types of building envelope distinguished by period of construction, considering the configuration with the median value of footprint area, SVF equal to 0.75, and N-S orientation, for a typical (a) and extreme (b) climate scenario in Brunico-Bruneck.

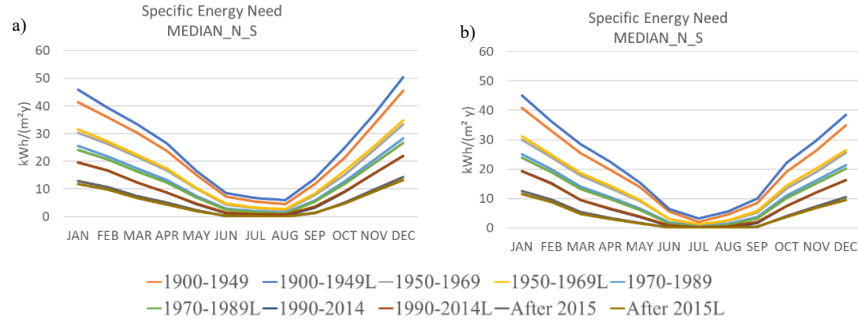


Fig. 3. Specific energy needs for space heating per period of construction for a typical (a) and extreme (b) climate scenario in Brunico-Bruneck for the building configuration with the median value of footprint area, S/V equal to 0.75, and N-S orientation

3 Archetype definition

3.1 Analysis of variance

Starting from the 210 building configurations and their energy performance in the four selected locations, simulated in both typical and extreme conditions, statistical techniques were applied to define building clusters sharing common characteristics and a smaller set of representative buildings for the analyzed Italian Alpine area. To achieve this goal, as a first step we performed an analysis of variance (ANOVA) to assess the influence of each considered variable on the simulated buildings' energy performance, in order to possibly reduce the complexity of the dataset. The influential parameters considered were chosen among the geometrical features presented in Table 1a, 1b, 1c and the envelope properties of Table 2.

Results from the ANOVA (Table 3) show that major factors and interactions have very high F -values, indicating a strong influence on the heating energy needs. In addition, the very small p -values indicate that all factors and interactions are statistically significant with respect to $\alpha = 0.01$. The results presented included the most significant factors and combinations (i.e., lowest p -value).

Table 3. ANOVA results with F -statistic and p -value for each factor and the main interactions

Factors	F -value	p -value
S/V	5568	$<2e^{-16}$
Area	248	$<2e^{-16}$
Orientation	4686	$<2e^{-16}$
U -value	73997	$<2e^{-16}$
HDD_{20}	18946	$<2e^{-16}$
Main interactions	F -value	p -value

S/V orientation	1896	$<2e^{-16}$
S/V U -value	2394	$<2e^{-16}$
Orientation U -value	1091	$<2e^{-16}$
U -value HDD_{20}	4033	$<2e^{-16}$

Table 4 shows that the strongest impact is related to the U -value, which has the most significant effect ($\eta^2 = 0.96$), explaining 96 % of the variance. Similarly, degree days (HDD_{20}) ($\eta^2 = 0.87$) has a significant impact, whereas S/V and orientation have a smaller influence. The least influential factor is the area, which has a very low influence ($\eta^2 = 0.08$), indicating that it does not play a substantial role. The main interactions between parameters are S/V | U -value (0.45), U -value | HDD_{20} (0.58), and S/V | orientation (0.40), which show that these combinations contribute significantly to the variance of the building energy performance. As confirmed by the confidence intervals, which provide a measure of uncertainty around the estimated η^2 , the most significant independent variables impacting on the heating energy performance of buildings are: average U -value, S/V , building floor area, and orientation.

Table 4. ANOVA results for η^2 partial effect

Factors	/	η^2	Confidence Interval	Interpretation
Main interactions				
S/V		0.66	[0.65, 1.00]	Moderate-high influence
Area		0.08	[0.06, 1.00]	Very low influence
Orientation		0.62	[0.60, 1.00]	Moderate-high influence
U -value		0.96	[0.96, 1.00]	Very high influence
HDD_{20}		0.87	[0.86, 1.00]	Very high influence
S/V orientation		0.40	[0.38, 1.00]	Moderate influence
S/V U -value		0.45	[0.43, 1.00]	Moderate influence
Orientation U -value		0.28	[0.25, 1.00]	Moderate-low influence
U -value HDD_{20}		0.58	[0.57, 1.00]	Moderate-high influence

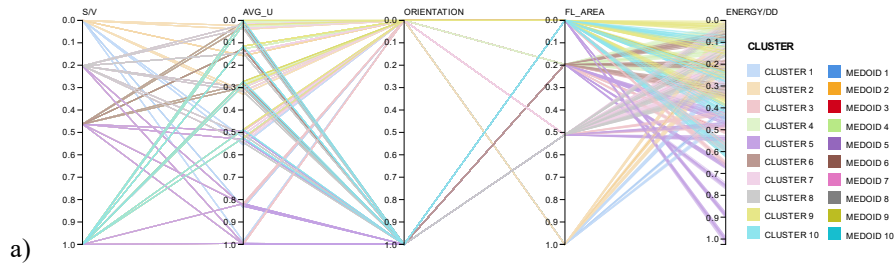
3.2 Clustering techniques

Once defined the representative variables through the ANOVA, the k -medoids clustering method was chosen because of its robustness against outliers and clear interpretability. We used Euclidean distances on normalized variables, including both building features (U -value, S/V , building floor area, and orientation) and energy performances in both typical and extreme climatic conditions (expressed in terms of annual specific energy needs per heating degree-days). Since the k -medoids clustering algorithm is based on the calculation of the distances between data points, variables have been normalized between 0 and 1 in order to prevent the potential distortion effects due to quantities with larger numerical ranges, which can dominate the distance calculation and modify the clustering results. After several trials,

each one characterized by a different number of divisions, 10 groups were selected. In fact, even increasing the number of cases, the variation in medoid values remains very close, resulting in no significant improvement in accuracy or added value to the analysis. Table 5 reports the results of k -medoids clustering. As observed, there is a high variability among the building features, such as the average U -value, which is categorized into low, medium, and high ranges, as well as the S/V ratio and the floor area, both with four different values. This diversity suggests that the chosen building archetypes properly represent the variability of the dataset and that the method is sensitive to variations in input parameters. Moreover, the clustering results (Figure 4a and 4b) highlight the presence of both compact and dispersed geometries, reinforcing the method's ability to distinguish different building typologies. With regard to specific energy needs, the calculated medoids span within a range of values, illustrating the diversity of energy performance across the identified archetypes. This wide coverage is particularly important for energy simulation studies, as it ensures that the archetypes can provide a representative basis for scenario analysis, retrofitting strategies, and policy recommendations.

Table 5. Coordinates of the medoids in the 10-medoid clustering

Medoids ID	S/V	Average U -value [W/(m ² K)]	Orientation	Floor area [m ²]	Annual specific energy needs per heating degree-days [Wh/(m ² y DD)]
1	0.39	1.43	N-S	1386.00	29.48
2	0.39	0.61	N-S	1386.00	19.65
3	0.56	1.98	N-S	445.63	52.48
4	0.56	0.55	N-S	445.63	20.82
5	0.56	1.98	W-E	445.63	65.65
6	0.56	0.55	W-E	445.63	26.37
7	0.47	0.91	N-S	813.75	21.78
8	0.47	0.91	W-E	813.75	27.15
9	0.74	0.85	N-S	216.00	28.54
10	0.74	0.85	W-E	216.00	42.59



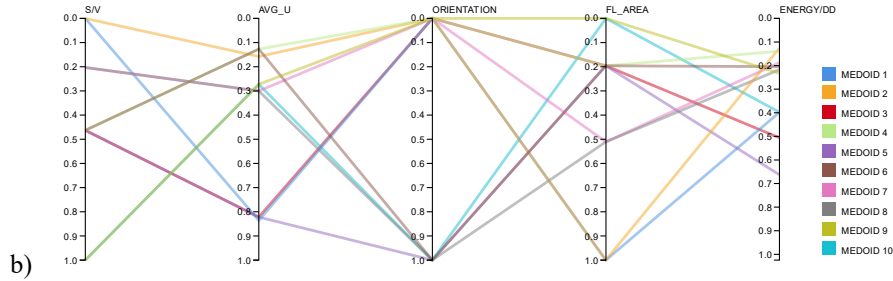


Fig. 4. Results of 10-medoids clustering: (a) composition (b) medoids

4 Conclusions

Due to the lack of information concerning the Alpine building stocks, this work proposed a statistical and simulation-based methodology to define representative buildings. Building geometry and energy performance characteristics were gathered and studied from datasets and literature information, using GIS tools and statistical analyses to determine the minimum set of parameters necessary to properly characterize the building stock. Once the significant variables were identified and evaluated, building energy performance simulations were used to determine the energy needs of each selected building in four different locations, considering typical and extreme weather conditions. After an ANOVA study performed to identify the most influential variables, these latter ones were used as input to clustering techniques (k -medoid clustering with Euclidean distances) to generate homogeneous groups and select the representative building archetypes.

The possibility of analyzing the behavior of a small number of representative buildings to predict the energy use profile of a large building stock was found particularly valuable, since it can provide reliable data to support energy retrofit planning. Furthermore, the inclusion of building performances under both typical and extreme climate conditions, allowed for the identification of a plurality of building configurations with different responses to various climate solicitations. This knowledge can enhance the climate resilience of both existing and future buildings within the stock, providing a highly replicable methodology that can be applied to other mountain regions or even urban areas with similar data scarcity challenges.

Future research could focus on incorporating real-time monitoring data to validate and improve predictive accuracy, contributing to broader climate adaptation strategies and energy-efficient building practices globally.

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