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Building in Historical Areas: Identity Values and Energy Performance of Innovative Massive Stone Envelopes with Reference to Traditional Building Solutions

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Abstract: The intrinsic nature of local rocks shaped the features of built heritage in historical centers. The resulting building culture is part of the cultural heritage itself, and must be considered when building in such areas, while it is essential to solve the issues related to traditional constructions' weaknesses. Nonetheless, the potentialities of massive stone envelopes, particularly the importance of thermal inertia, have contributed to redefining the language of contemporary architectural culture. Nowadays, although the trend of employing thin stone cladding panels is prevalent, thick stone envelopes are gaining a renewed importance. Previous literature demonstrated that mixed building technologies or massive stone envelopes coupled with load-bearing framed structures are able to meet comfort and safety requirements and to guarantee the integration of new constructions in the consolidated urban landscape, avoiding historicist approaches. This research, through the analysis of case studies, aims to describe innovative building solutions developed by contemporary architectural culture, comparing them with traditional stone masonry walls. Moreover, thermal energy performance of such building solutions is assessed through dynamic yearly simulations. Results show that these solutions are technically and architecturally suitable to build in historical centers, because they can express urban cultural identity and guarantee good energy performance and users' comfort.

Keywords: innovative stone envelopes; traditional stone masonry; cultural identity; architectural identity; thermal energy performance; thermal inertia; dynamic yearly simulation

1. Introduction

Stone, together with wood, has had a central role in architecture and constructions. In many European areas, stone materials characterized the traditional construction culture and the historical built environment. In Italy in particular, many smaller urban centers and bigger urban areas are built with stone as primary and most prominent material. Each of these areas is characterized by particular types of stone, since in previous eras it was common to employ the materials that were available in the area, "km0". Some examples are "leccese" stone envelopes in the Salento region, or "ardesia" (i.e., slate) stone roofs and dry-walls in the Liguria region. Moreover, stone variety in Italian peninsula panorama contributed to differentiating and strongly connoting even geographically close urban areas such as Siracusa, Catania and Messina in the Sicilian region or Sanremo, Genova and Savona in the Liguria region [1]. The use of same-stone materials for different construction elements contributes to achieving harmony, so that such urban centers were defined as art masterpieces [1]. Focusing on walls, the most common construction technology is the single-layer stone masonry. Therefore, the stone layer has both the structural function and the role of separating indoor areas from outdoors in order to maintain acceptable thermal comfort for the occupants. The knowledge of traditional construction technologies and solutions is vital to maintain the identity and peculiarity of the context-specific construction culture and to define refurbishment or construction interventions in historical areas. However, the fragilities and weak points of such traditional technologies need to be overcame in order to guarantee safety and comfort standards to occupants, while still maintaining identity.

In terms of safety, historical stone constructions are often lacking the sufficient requirements to guarantee occupants' safety in the occurrence of earthquakes. The non-homogeneity of the structure, which is linked to construction methods and lack of connections does not allow the wall to achieve a monolithic behavior in case of horizontal actions. The wall is therefore subjected to collapse for the disintegration of the stone masonry, for the reversal or for the out-of-plane bending mechanisms, as well as for shear or buckling.

Referring to thermal energy performance, traditional single-layer masonry presents critical situations in winter due to poor insulation: research based on on-site monitoring of traditional stone buildings has shown that stone envelopes are not able to provide sufficient thermal comfort without heating systems, even if they keep the internal temperature more stable than lightweight ones [2]; another study [3], again based on on-site investigations, has shown that thermal transmittance values of traditional stone envelopes range from 1.25 to 1.70 $W/(m^2 \cdot K)$, far higher than the limit values imposed by the Italian energy-saving regulations [4]. As a consequence, previous research has stressed the need to improve the energy efficiency of existing buildings characterized by traditional stone envelopes, and has assessed the effects of insulation in terms of thermal comfort and energy consumption [3,5,6].

Indeed, such traditional construction technology allows the achievement of determined benefits, which are connected not only to the architectural value, but also to the environmental sustainability of massive stone as reported below.

In terms of architectural expression and values, the employment of local stone materials in the form of thick layers permits the integration of the building in the natural or urban environment, as well as interpretation of local identity [7]. In fact, the quality of the locally available stone materials strongly influenced the peculiarities and characteristics of the built environment and construction technologies. Therefore, massive stone envelopes are able to maintain a certain identity value; thin stone construction elements are instead easier to carry and consequently they can more conveniently be employed in construction sites that are farther from the quarry, and, as a result, they lose the landscape-specific expressive power.

The environmental sustainability of massive stone construction elements and buildings has been demonstrated by previous research, as discussed in the next paragraphs of this section. The employment of thick stone elements allows the obtaining of durable constructions with high thermal inertia, which are also easily recyclable or obtained by means of reuse or recycle themselves.

With respect to durability, the employment of durable materials such as stone is able to increase the construction's life and to reduce the environmental impact of the construction [8]. Thin stone construction elements are more sensible to the external environment and degradation than thick stone elements, and their degradation has been assessed both in terms of aesthetics [9] and thermal energy performance [10] in previous research.

Moreover, the massive single-layer stone masonry is characterized by high thermal inertia, when the importance of this characteristic has been recognized by national regulations about energy saving in buildings [4,11]. To confirm such value, studies based on dynamic simulations and on-site monitoring have proved that massive envelopes are able to ensure a considerable reduction of indoor thermal discomfort during summer [12,13]. Other researchers [14] have shown that the difference in terms of energy demand in buildings characterized by low-inertia walls compared to high-inertia ones is as high as 20% for cooling energy demand and equal to almost 10% in terms of heating energy demand, with high-inertia envelopes allowing energy savings. Furthermore, it has been stressed that it is impossible to design energy-efficient buildings using only an U-value-based approach and that the role of thermal inertia, i.e., the positive effect of thermal capacity, appears to be relevant in particular for moderate climates [15]. Moreover, massive stone envelopes could be realized with the gabion building technique, which offers the potential to reuse or recycle local stone waste produced in stone plants or during the demolition of existing constructions [16]. The use of waste generated at the quarrying site during the extraction of natural stones or at the processing units is essential to reduce the environmental impact of stone industry due to the large quantities of generated waste compared to the effectively used building materials [17,18]. More specifically, the use of stone waste demonstrated its potential to improve outdoor thermal comfort when applied in the built environment [19].

The expressive and technical potential of massive stone have been widely recognized by contemporary architectural culture. Thin stone construction elements still represent the major trend, but numerous designers rediscovered massive stone walls, employing mixed technologies, masonry or gabion techniques. These technical solutions promote the expressive potential, durability and thermal inertia of traditional stone systems, but they are based on multiple-layers wall system and are therefore able to overcome thermal energy performance weaknesses. Furthermore, gabion construction elements realized with stone waste limit disposal problems and avoid the depletion of non-renewable natural resources. Moreover, the adoption of mixed stone-concrete technologies and the possibility to couple stone envelopes to steel or reinforced concrete load-bearing structures guarantees higher levels of safety in case of seismic events.

Given all these considerations, the present research analyzes the technological features of some of the innovative construction solutions, chosen among the most representative ones in terms of contemporary architectural culture. Such solutions are carefully selected and analyzed both under the technical point of view and in terms of thermal energy performance. A comparison with the thermal energy performance of traditional stone masonry was carried out too, to evaluate thermal energy benefits that are connected with such contemporary massive stone envelopes.

The present research fills a gap in the literature about stone envelopes since, to the best of the authors' knowledge, the integrated technical/thermal energy performance approach was not adopted in previous studies to investigate innovative stone construction elements. The innovative aspect of the work, indeed, is connected to the simultaneous consideration of different aspects of massive stone envelopes employed in contemporary constructions, such as their expressive potentialities, their technical features and the environmental benefits related to their thermal energy performance.

Results of these analyses demonstrate that the above mentioned envelopes can be applied in new constructions to be built in historical areas, since they manage to promote local building culture and at the same time improve the thermal energy performance, according to contemporary needs.

2. Methods

For the present research, an in-depth analysis of previous literature and state-of-the-art massive stone envelope architectures was carried out and three building were selected as case studies. These are the Vals thermal bath by Peter Zumthor [20–23], the High Musical Studies School of Galicia by Antón García-Abril Ruiz [24,25] and the Haus 9 × 9 by Titus Bernhard [16,25,26] (Figure 1).

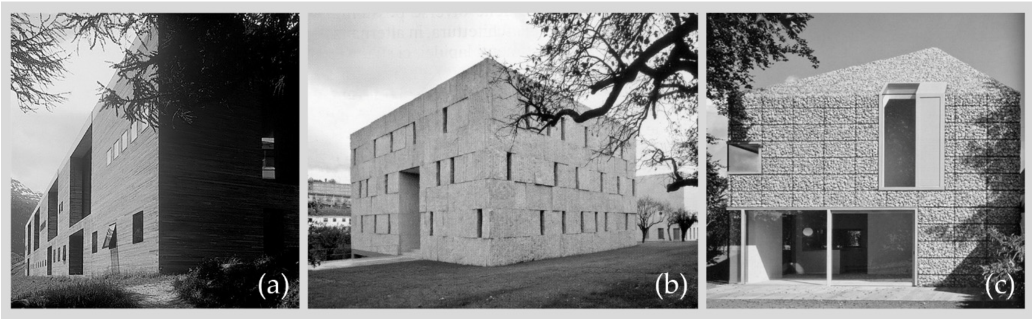


Figure 1. Building case studies: (**a**) Vals thermal bath (adapted from [20] (p. 161)); (**b**) High Musical Studies School of Galicia (adapted from [25] (p. 73)); (**c**) Haus 9 × 9 (adapted from [25] (p. 36)).

In these buildings, in fact, the adoption of mixed stone-concrete technology and the combination of stone envelopes with steel or reinforced concrete load-bearing structures guarantees higher levels of safety in case of seismic events with respect to traditional stone envelopes. Furthermore, stone is used in combination with internal layers made of other materials that enhance the thermal and energy performance of the building.

Moreover, the envelopes of the selected case studies are among the most interesting stone building solutions developed by the contemporary architectural culture, in terms both of architectural expression and technological solution, as demonstrated by the large diffusion they had on architectural journals [16,20–26]. Finally, they can be hypothetically employed in different building typologies, even if the convenience of such possibility has to be carefully considered for each case.

In the next sections, the three building solutions have been analyzed under the technological and performance perspectives, in order to highlight their main features and potentialities. First, the technological solutions were considered and described. Then, a case study building project was selected to perform the dynamic simulation for the assessment of the thermal energy performance of the different kinds of envelope.

With respect to thermal energy performance assessment, the case study buildings were modeled on the interface software "Design Builder" (Version 5.0.3.007): this software runs EnergyPlus, one of the most widely used building energy analysis tools [10,27,28], as a simulation engine. Multiple yearly dynamic simulations were carried out for comparison purposes, to evaluate the possible energy savings achieved thanks to the application of such innovative stone envelopes with respect to traditional stone masonry solutions. Furthermore, numerical results were analyzed and compared. Finally, an economic analysis was carried out in order to compare the HVAC energy consumption of the selected case studies with the implementation costs of the stone envelope building solutions, similarly to Salata and colleagues evaluation [29].

Each of these steps is more precisely described in the next sections.

2.1. Innovative Stone Massive Envelope Selection

From the last years of the 20th century, masonry and gabion building techniques are being used by designers to realize massive stone envelopes.

Masonry walls were poorly promoted in the architectural culture after the introduction of load-bearing framed structures made of steel or reinforced concrete and only after the Second World War in France there was a new interest in load-bearing stone walls thanks to the efforts of F. Pouillon and P. Abrahm [30]. Nowadays, however, stone is used by many designers to build single layer, multiple layers and composite load-bearing masonry walls, as well as self-supporting masonry walls.

Vals thermal bath and High Musical Studies School of Galicia are among the contemporary works characterized by composite load-bearing masonry walls and self-supporting masonry envelopes respectively. In Vals thermal bath (1994–1996, Vals, Switzerland) [20–23] Peter Zumthor, the designer, has chosen to employ the locally quarried gneiss to establish a strong relationship with the mountain landscape. The load-bearing walls, in fact, are characterized by an external massive stone cladding (0.12–0.15 m), which was realized with slats of various dimensions. The stone elements were laid with a synthetic adhesive. The cladding is incorporated in the inner reinforced concrete core of the walls, and it was also employed as a formwork for the concrete. The building solution designed by the architect has been defined by critics as "Vals composite masonry" [20–22] because it is based both on ashlar masonry technique and on reinforced masonry technique and because the cladding contributes to the structural behavior of the walls.

The High Musical Studies School of Galicia (1999–2004, Santiago de Compostela, Spain) [24,25] by García-Abril is characterized by Mondariz Granite, again, a locally quarried stone that has been traditionally used in Galician architecture. The designer has chosen to employ this building material to rediscover its tectonic qualities and to create a strong connection between the architecture and the surrounding landscape. In fact, the walls that are tangent to the steel framed structure of the building are made of large granite slabs, which are 0.30–0.35 m thick, 1.75 m high and have variable widths. The slabs were obtained starting from blocks with twice the final slab thickness (thus, around 0.70 m), by means of drilling. Drilling separation signs are still visible on the stone surface of the slabs. The slabs were then laid, without any mortar, in regular courses and were bonded to each other by stabilizing brackets on all sides: it would be necessary to connect the slabs to the steel structure in order to improve the behavior of the walls under horizontal loading. The rear faces of the granite slabs were sprayed with 4 cm of polyurethane, to improve thermal insulation. The envelope was completed installing a backing of Pladur Metal plasterboard and a mineral wool layer, which are separated by a large air gap from the external layers of the walls.

With respect to gabion technique, it was originally developed for soil retaining walls, and has been used in architecture since the last decade of the 20th century to build self-supporting walls: many designers, such as Ian Ritchie, John Smart and Herzog and De Meuron, in fact, have recognized and explored their environmental and aesthetic values [16,31]. From the late 90s gabion modules started to be employed for massive stone claddings connected to the load-bearing structure of the building. The Haus 9 × 9 building [16,25,26] is representative of this technical innovation. This single-family residential building (2002–2003, Augsburg, Germany) by Titus Bernhard has been realized with wire mesh gabion building modules filled with dolomite stone fragments. The designer has chosen gabion building technique "as a statement against banal local design statutes" [32]. Moreover, he decided to employ gabion as a non-load-bearing massive cladding to ensure high thermal insulation levels. Gabion building modules, which covers also the sloped roof of the house, measure 1.00 m × 0.50 m× 0.12 m and are suspended from the reinforced concrete load-bearing structure through metal hooks, which are fixed to a rear steel structure. A waterproof drainage mat, 0.01 m thick, an extruded rigid foam polystyrene insulation, 0.14 cm thick, and a bitumen coat, 0.005 m thick, were inserted between the concrete load-bearing structure of the building and the gabion cladding.

As above mentioned, such buildings are selected as representative of the innovative stone construction techniques due to their peculiar stone envelope coupled with concrete or steel load-bearing structures, and due to the huge diffusion on architectural journals as contemporary stone architectures. While the latter example, Haus 9 × 9 is a residential building, both Vals thermal building and the School of High Musical studies in Galicia are non-residential buildings: this could start a discussion with respect to building typology and the selected envelopes, which is a future development of the present study, but that is not considered for this study purposes. Here an abstraction has been performed, since the main objective was to consider technical and thermal energy performance.

2.2. Case Study Building Definition, Dynamic Simulation and Economic Analysis

The simulations were performed on a regular-shaped residential building, especially designed to recall the features of the traditional terraced houses that characterize many historical urban centers in Italy. The case study is a two-storey building project, which can be considered for new constructions in historical areas as well as reconstruction in case of damaged buildings. It has a sloped roof and two of the four walls are adjacent to existing buildings and were considered as adiabatic. This simplified approach for simulating the boundary conditions of adjacent buildings was adopted after a sensitivity analysis. Indeed, the software does not allow modeling of heat flows and temperatures on two adjacent buildings simultaneously and to model the energy transfer between them. Two solutions are suggested to solve this limit: the first one consists in modeling the walls between the two different buildings as adiabatic. The software guide reports that this solution is able to provide accurate results if the temperatures of the adjacent buildings are similar, which is the case of our case study, and is specifically suggested if only the actual building is taken into account. The second solution requires to model the different buildings as parts of the same building and then separate the results after the simulation (by considering the individual "blocks"). This solution is suggested if all the adjacent buildings are investigated. Therefore, we decided to model both the cases in order to perform a sensitivity analysis on the thermal inertia indicators i.e., time lag and decrement factor. Given that results only had a negligible variation (for time lag there was no difference, and for the decrement factor the variation was in the order of 0.000), we decided to employ the first of the suggested solutions, i.e., the one with adiabatic transversal walls, since it represents a compromise between accuracy and computational time. Another aspect that we considered in this choice to simplify the model was the consideration that the focus of the present research is a comparative analysis between different envelopes, that were all modeled on the same case study, with the same characteristics except for the composition of the longitudinal walls envelope.

The longitudinal south- and north-facing walls have four openings each. In Figure 2, the plans, the facade and a cross-section of the building are illustrated.

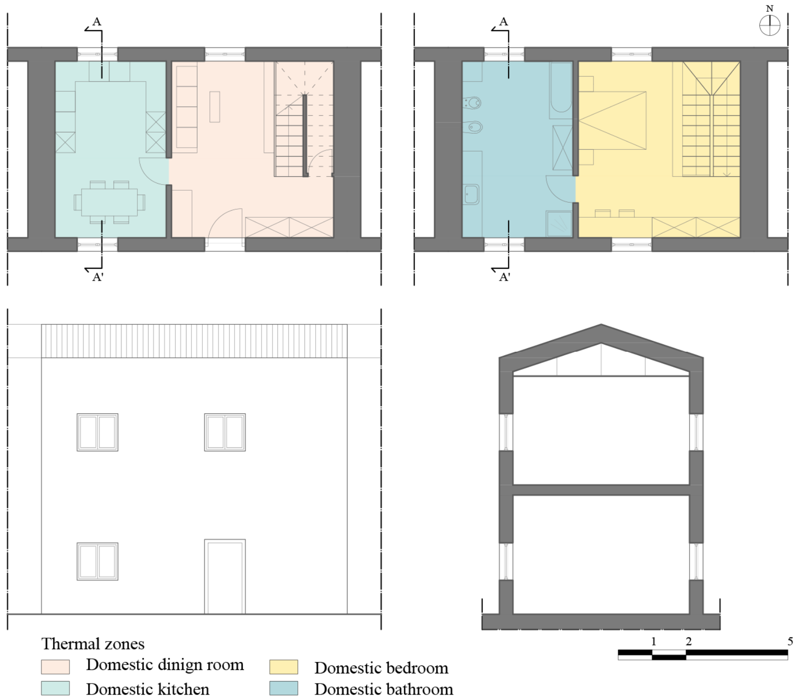


Figure 2. Ground-floor and first-floor plans, front facade and AA' cross section of the building project.

The case study building is located in Grosseto, Italy, which could well represent such residential typology and stone identity. Therefore, Grosseto weather data were employed for the simulation. The city of Grosseto is located in the central Italian region of Tuscany and it is characterized by 1550-degree days. Therefore, according to the Italian climate zone classification established by the Decree of the President of the Republic of Italy of 26 August 1993, n. 412, it is in the climate zone D.

According to the Köppen classification system [33], the city has a humid subtropical climate (Cfa). The external hourly temperatures, input of the dynamic simulation, are graphed in Figure 3, while the mean monthly temperature are reported in Table 1.

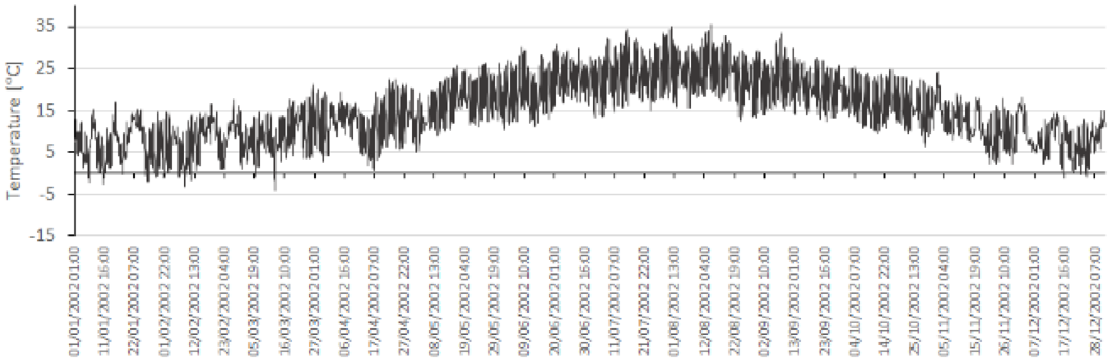


Figure 3. Air temperature in Grosseto, Italy, input of the dynamic simulations.

Table 1. Mean monthly temperature in Grosseto, Italy.

WMO Station Identifier 162,060							**Latitude: 42.75; Longitude 11.07**					
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outside Dry-Bulb Temperature (°C)	6.9	7.8	9.3	12.4	16.7	20.6	23.6	23.7	20.8	16.3	11.4	8.1

The physical characteristics of the building have been described within the dynamic simulation environment by modeling the construction elements (Table 2) and the occupancy schedules (Table 3). The thermal transmittance of the construction elements listed in Table 2 are lower than the limit U values set by the Italian building regulation for the climate zone “D”, which are 0.32 W/(m^2·K) for flat or sloped roof elements, 0.36 W/(m^2·K) for floor elements adjacent to non-heated areas and 2.4 W/(m^2·K) for transparent elements [4]. The occupancy schedules for each thermal zones were compiled specifically for residential buildings, by checking each room activities from previous literature [10,34] and from Design Builder/EnergyPlus. In these schedules, the electric equipment gain and the target illuminance were also specified according to the activities assigned to each room.

Table 2. Thermal characteristics of the construction elements.

Construction Element	Materials	Thickness	Thermal Transmittance
Ground floor	Timber flooring Floor screed Glass fiber insulation Concrete	0.03 m 0.07 m 0.15 m 0.2 m	0.20 W/(m^2·K)
Internal floor	Timber flooring Floor screed Concrete	0.03 m 0.07 m 0.2 m	0.52 W/(m^2·K)
False ceiling	Plasterborad	0.03 m	2.19 W/(m^2·K)
Roof	Clay tile Roofing felt Stone wool Concrete	0.025 m 0.005 m 0.24 m 0.25 m	0.13 W/(m^2·K)
Partition	Gypsum plasterboard Air gap Gypsum plasterboard	0.025 m 0.1 m 0.025 m	1.64 W/(m^2·K)
Windows	PYR B clear Air PYR B clear	0.003 m 0.013 m 0.003 m	1.96 W/(m^2·K)

Table 3. Indoor activity schedules of the case study.

Thermal Zone	Characteristics
1. Domestic dining room (ground floor)	Density: 0.017 people/m^2 Activity metabolic rate: eating-drinking 110 W/person Target illuminance: 150 lux Equipment gain: 3.06 W/m^2, radiant fraction 20% Schedule: from 6:00 am to 10:00 am and from 6:00 pm to 10:00 pm, 7 days/week
2. Domestic kitchen (ground floor)	Density: 0.024 people/m^2 Activity metabolic rate: work involving walking etc 160 W/person Target illuminance: 300 lux Equipment gain: 30.28 W/m^2, radiant fraction 20% Schedule: from 7:00 am to 10:00 am and from 7:00 pm to 11:00 pm, 7 days/week
3. Domestic bedroom (first floor)	Density: 0.023 people/m^2 Activity metabolic rate: bedroom 90 W/person Target illuminance: 100 lux Equipment gain: 3.58 W/m^2, radiant fraction 20% Schedule: from 10:00 pm to 9:00 am, 7 days/week
4. Domestic bathroom (first floor)	Density: 0.019 people/m^2 Activity metabolic rate: light work 120 W/person Target illuminance: 150 lux Equipment gain: 1.67 W/m^2, radiant fraction 20% Schedule: from 7:00 am to 10:00 am and from 7:00 pm to 11:00 pm, 7 days/week

The heat exchange with the ground was modeled with the default ground temperature mechanism, using ground monthly temperatures, as other studies did with the same software [35]. More accurate modeling approaches for ground heat transfer were presented in the work of Mateus and colleagues [36] in which a sensitivity analysis on the impact of this simulation option was performed. The tested modeling approaches of the cited work are the SLAB EnergyPlus ground coupling auxiliary model and an alternative method that uses the 2-m depth ground temperature and considers a 2-m depth floor slab construction that includes a layer of 1.7 m of ground material. In the present work, a sensitivity analysis was performed on one of the case studies, the reference case study T[40], in order to estimate the error connected to the adoption of the simplified ground heat transfer modeling approach. It was found that the results obtained using the SLAB method differ only marginally from the ones assessed with the simplified approach: the difference in the energy requirements results is lower than 2% while the value of time lag and of the decrement factor do not change. Therefore, the simplified method based on ground monthly temperatures was selected because it provided sufficient precision for the purposes of the present work. The infiltration rate was set to 0.7 volume per hour and the natural ventilation was modeled for each thermal zone using the relative schedule. Moreover, the mixed mode setting was employed in order to disable the HVAC system when the natural ventilation was sufficient.

The HVAC (heating, ventilation and air conditioning) system was specified in the simulation software in order to assess the total annual energy requirement, the monthly heating and cooling energy demand and the heat gain and loss energy through the walls. The HVAC template "Radiator heating, Boiler HW, Mixed mode Natural Ventilation, Local comfort cooling" was selected: it comprises radiators (inlet air maximum temperature 35 °C; Coefficient of Performance 0.85), a boiler for hot water (inlet water temperature 10 °C; outlet water temperature 65 °C; CoP 0.85) and an air conditioning system (inlet air minimum temperature 12 °C; CoP 1.80). The heating is fueled by means of natural gas while the cooling system employs electricity from grid. The set point temperatures of the HVAC system were selected as 20 °C in winter and 26 °C in summer, as suggested by Italian Organization for Standardization and Comité Européen de Normalisation, UNI EN 15251, and as from previous literature [34].

The simulations were also performed in free-running conditions with the HVAC system turned off, in order to analyze the thermal performance of the building with varying stone envelopes. The indoor operative temperatures were assessed on the coldest (12 January) and the hottest (31 July) days of the year. The same summer day was chosen also to evaluate the external and internal surface temperature fluctuations of the south-facing external walls. Finally, the thermal inertia of the same walls was characterized by two dynamic indicators, the time lag (φ) and the decrement factor (f). Such indicators were evaluated considering the maximum and the minimum values of internal and external surface temperature of the south-facing external walls, according to the following equations (Equations (1) and (2)) [13]:

$$\begin{aligned} \varphi &= |t_2 - t_1| \\ \text{at } t_1 \;\; T^s_{int}(t_1) &= T^s_{max,int} \\ \text{at } t_2 \;\; T^s_{ext}(t_2) &= T^s_{max,ext} \end{aligned} \tag{1}$$

$$f = \frac{A_{si}}{A_{se}} = \frac{T^s_{max,int} - T^s_{min,int}}{T^s_{max,est} - T^s_{min,est}} \tag{2}$$

Given the above described case study building and systems, multiple simulations were performed by only varying the external walls of the building project model and keeping the other construction elements and occupancy schedules unvaried, so that the differences in the thermal energy performance are ascribable only to the stone envelopes. More specifically, the same layers of the selected innovative massive stone envelopes were applied to the model. The features of the different types of external vertical wall assemblies, which characterize the simulated case studies, are summarized in Figure 4.

Two of the simulations (case T[40], case T[80]) were carried out on models with traditional stone masonry walls, where squared blocks are arranged according to the *opus quadratum* construction technique. These walls differ from each other only for their thickness: the envelope of the case T[40] is 0.415 m thick, while the one of the case T[80] is 0.815 m thick. Both of them are internally finished by means of a thin plaster layer. The letter "T" indicates "Traditional", while the numbers recall wall thickness.

Instead, three case studies are characterized by the innovative stone massive envelopes that were above described and that were employed in the architectures designed by Zumthor (case I[Zum]), Abril (case I[Abr]) and Bernhard (case I[Ber]). The letter "I" indicates "Innovative", while the name of the designers is recalled to identify the technology employed in the simulation, which replicate the one of the existing, above mentioned constructions. These three wall assemblies were defined taking into consideration the construction details of the buildings that were published [22,24,26].

The thermal energy performance of the "innovative" case studies I[Zum], I[Abr] and I[Ber] was compared with the performance of the "traditional" case studies T[40] and T[80], which have been chosen as reference cases.

The HVAC energy consumptions obtained as results of the energy performance study were employed to carry out an economic analysis. These data, indeed, were compared with the implementation costs of the stone envelope building solution of each case study.

Firstly, the approximate costs per square meter (€/m^2) for the external wall solutions used in the selected case studies were estimated according to the unit costs collected in the Lazio Region Price List (*Tariffa dei prezzi 2012 Regione Lazio* [37]), an official Italian Price List approved with the D.G.R. 412/6 August 2012 in the Lazio region. Furthermore, the total costs for the construction of the entire envelope of the different case studies were evaluated and the differences between the cost of the case T[40] and the costs of the cases T[80], I[Zum], I[Abr] and I[Ber] were assessed.

Secondly, the annual costs for heating and cooling were evaluated according to the unit costs of the fuels used to power the HVAC systems, i.e., electricity and natural gas, available on the website of the Italian Authority for Electric Energy Gas and Hydric Systems [38]. The assumed electricity cost is 0.17 €/kWh while the assumed natural gas cost is 0.73 € per standard cubic meter. Moreover, the annual savings with reference to the case T[40] were assessed.

Finally, the number of years that are necessary to balance the greater construction cost of the innovative envelope solutions with the related annual energy savings was calculated.

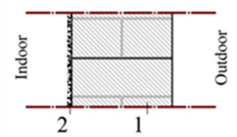
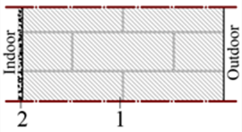
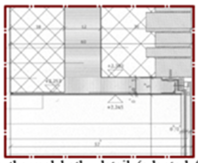
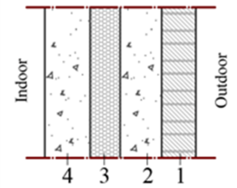
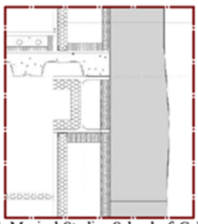
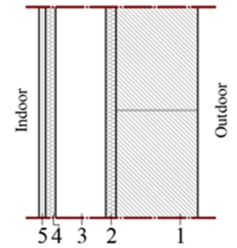
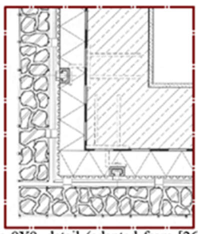
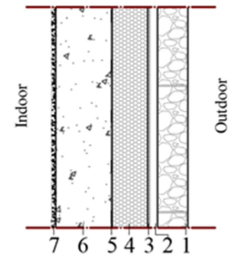
	Detail of the reference building	Cross section of the analyzed wall assembly	Materials	t (m)	U (W/(m²·K))
Case T[40]			1_Stone masonry with mortar (0.40 m) 2_plaster (0.015 m)	0.41	2.01
Case T[80]			1_stone masonry with mortar (0.8 m) 2_plaster (0.015 m)	0.81	1.3
Case I[Zum]	 Vals thermal bath, detail (adapted from [22] (p.75))		1_stone cladding (0.135 m) 2_reinforced concrete (0.165 m) 3_expanded polystyrene (0.12 m) 4_reinforced concrete (0.18 m)	0.6	0.3
Case I[Abr]	 High Musical Studies School of Galicia, detail (adapted from [24] (p. 132))		1_stone cladding (0.325 m) 2_mineral wool (0.04 m) 3_air chamber (0.2 m) 4_polyurethane (0.04 cm) 5_plasterboard (0.013+0.013 m)	0.63	0.33
Case I[Ber]	 Haus 9X9, detail (adapted from [26] (p. 1276))		1_gabions (0.12 m) 2_air chamber (0.03 m) 3_drainage mat (0.01 m) 4_polystyrene insulation (0.14 m) 5_bitumen coat (0.005 m) 6_reinforced concrete (0.22 m) 7_plaster (0.015 m)	0.54	0.20

Figure 4. Case studies: reference buildings, cross section of the wall assemblies, materials, total thickness (t), thermal transmittance (U).

3. Results

3.1. Energy Performace

The results obtained by means of the dynamic simulations demonstrated that the innovative building solutions (cases I[Zum], I[Abr] and I[Ber]) are able to ensure lower total annual energy consumption compared to the reference cases T[40] and T[80] (Table 4), due to their lower thermal transmittance. With reference to the energy consumption of the case T[40], in fact, the energy savings of the innovative solutions are far higher than the ones of the case T[80], with the former ranging from 29.4% to 32.6%, while the latter permits a saving of 7.8% of total site energy with respect to case T[40].

Table 4. Total annual site energy consumption of the five case studies.

Energy	Case T[40]	Case T[80]	Case I[Zum]	Case I[Abr]	Case I[Ber]
Total site energy (kWh)	11,981.5	11,052.6	8259.0	8464.7	8075.7
Energy savings with reference to the case T[40] (%)	-	7.8	31.1	29.4	32.6

By now considering separately the energy consumption for heating and for cooling, the innovative solutions are more advantageous than the traditional ones in terms of heating, as showed in Figure 5. With reference to case T[40], in fact, the energy savings of the cases I[Zum], I[Abr] and I[Ber] range from 47.9% up to 53.8%.

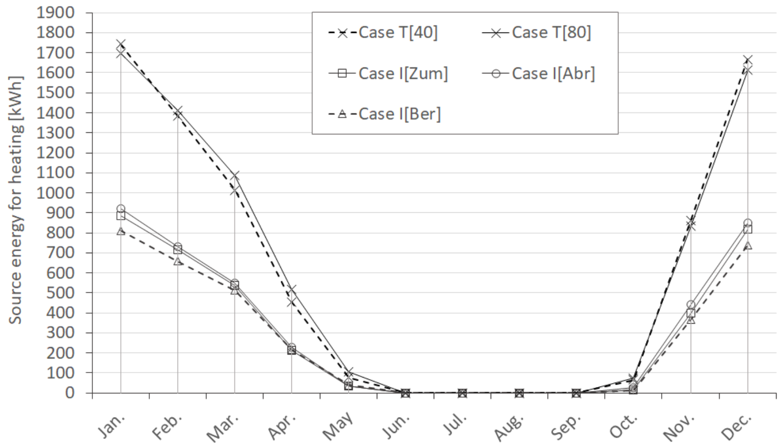


Figure 5. Source energy monthly requirement for heating.

The differences between the cooling energy consumption of cases I[Zum], I[Abr] and I[Ber] and cases T[40] and T[80] are relevant too, even if lower than that ones observed for heating energy, in particular during August (Figure 6). With reference to case T[40], in fact, the annual savings of the cases I[Zum], I[Abr] and I[Ber] range from 19.6% up to 39.8%.

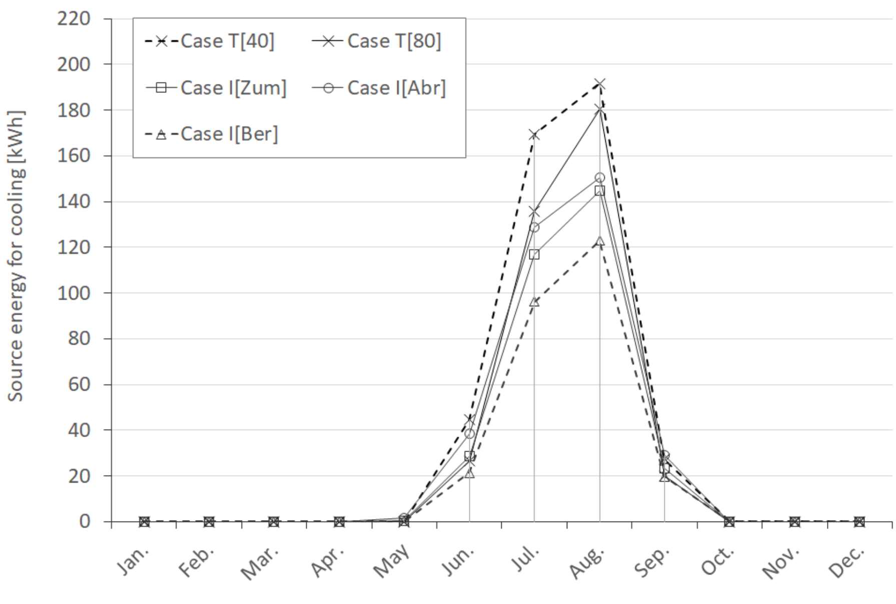


Figure 6. Source energy monthly requirement for cooling.

As for the heat gain/loss through the walls, innovative envelopes are able to guarantee a better performance, since they reduce the heat losses compared to traditional solutions. This is due to their lower thermal transmittance (Figure 7).

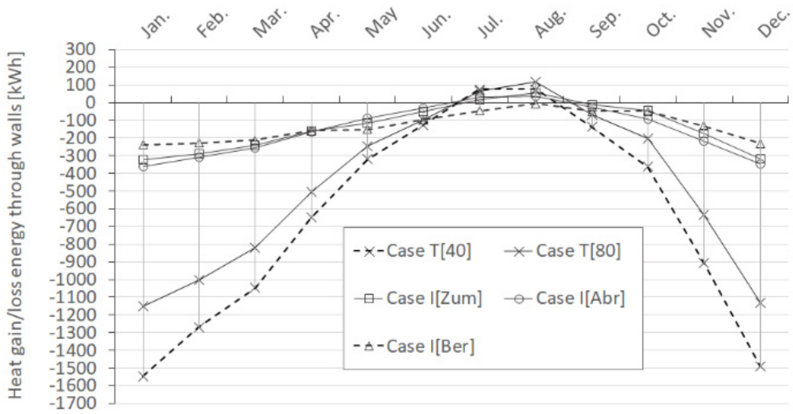


Figure 7. Monthly heat gain/loss through the walls.

3.2. Thermal Performance

The thermal performance of the different case studies was assessed by means of dynamic simulations that were carried out in free-running conditions, i.e., with HVAC turned off so that the obtained results are not affected by energy systems but are only influenced by the features of the walls. Results show that the envelope adopted in the case I[Ber] ensures the best level of indoor thermal comfort both in winter and in summer. The operative temperatures assessed during the coldest and on the hottest days of the year, in fact, are respectively the highest and the lowest (Figure 8) consistently all along the day. In any case, also in the best scenario, there is the need to couple active systems with passive ones (such as wall insulation) to achieve suitable thermal comfort conditions for the inhabitants. However, such HVAC-off simulations allow observation of the bare data about wall thermal performance. The winter thermal performance of the different case studies is strongly related to their thermal transmittance: as expected, indeed, the lower is the thermal transmittance of the vertical walls the higher is the operative temperature reached inside the building and therefore the better the thermal performance of the stone envelope.

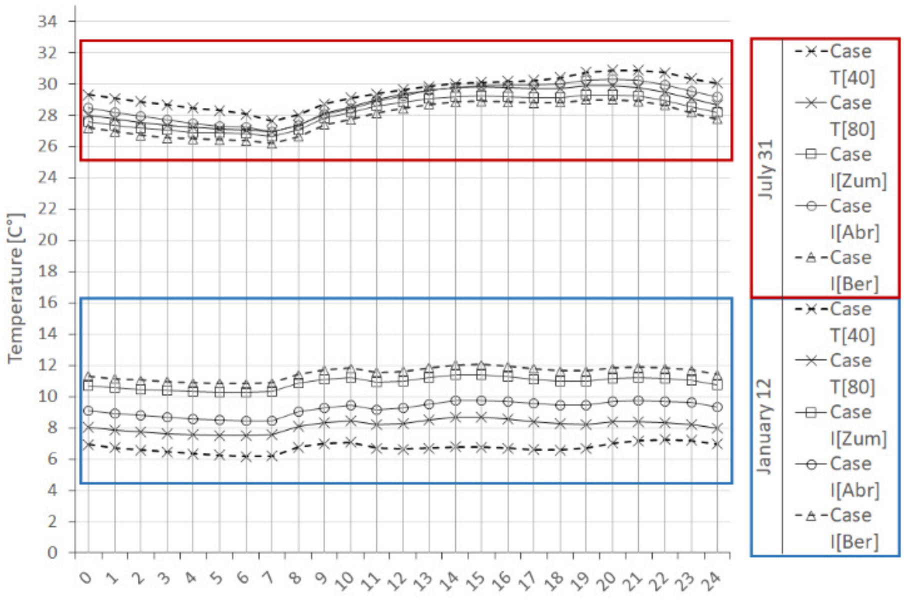


Figure 8. Operative temperatures assessed inside the building for each hour of the coldest (12th January) and of the hottest (31 July) days of the year.

While the winter thermal performance is mainly affected by thermal transmittance values, during summer, the position of the thermal insulation layer in the wall assembly is another important factor that cannot be ignored. In fact, as can be noticed from Figure 8, case I[Abr], while having a thermal transmittance equal to 0.33 W/(m^2K), lower than case T[80], displayed worse thermal performance during summer. As already discussed in previous literature [39,40], this is due to the positioning of the thermal insulation layer at the inner side of the thermal mass, which during summer causes heat to stay inside the building and overheats the indoor space. Indeed, in the review conducted from Verbeke and colleague [39] it was concluded that for most of the buildings and climates, higher amounts of thermal mass at the inner side of the thermal insulation appear to be beneficial with regard to improving thermal comfort and reducing the energy demand. Moreover, in the work of Stazi and colleagues [40] the application of internal thermal insulation as a retrofit strategy of a high thermal mass house was proved to be more detrimental for comfort in summer than the use of external insulation because it causes more severe overheating.

The summer thermal performance of the different case studies was examined analyzing also the surface temperatures of the relative south walls. This analysis shows that the internal surface temperatures of the models have far lower fluctuation than the external ones (Figures 9–13), meaning that the walls are able to attenuate extreme external conditions. The envelope of the case I[Ber] determines the lowest internal surface temperature while the one of the case T[40] displayed the highest internal surface temperature (Figure 14). As observed in the analysis of the operative temperature, the case I[Ab] shows the worst performance among the innovative cases due to the position of the thermal insulation in the wall assembly.

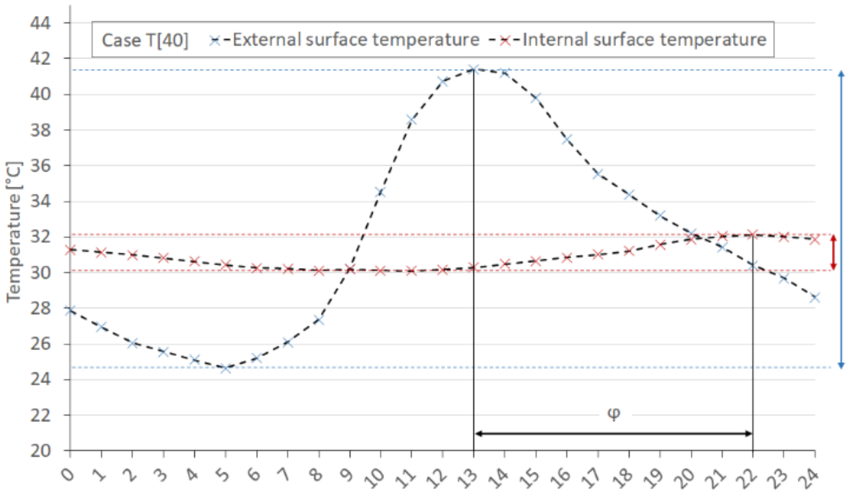


Figure 9. The fluctuation of the internal and external surface temperatures of the south wall of the case T[40] assessed on 31 July.

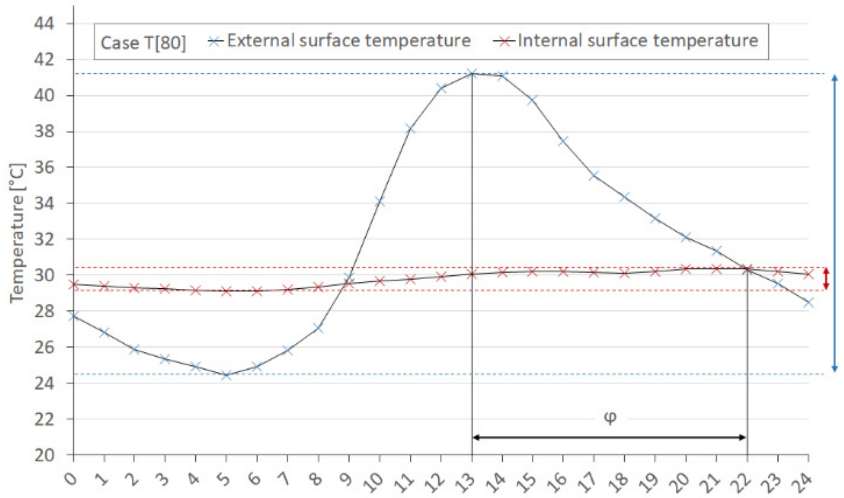


Figure 10. The fluctuation of the internal and external surface temperatures of the south wall of the case T[80] assessed on 31 July.

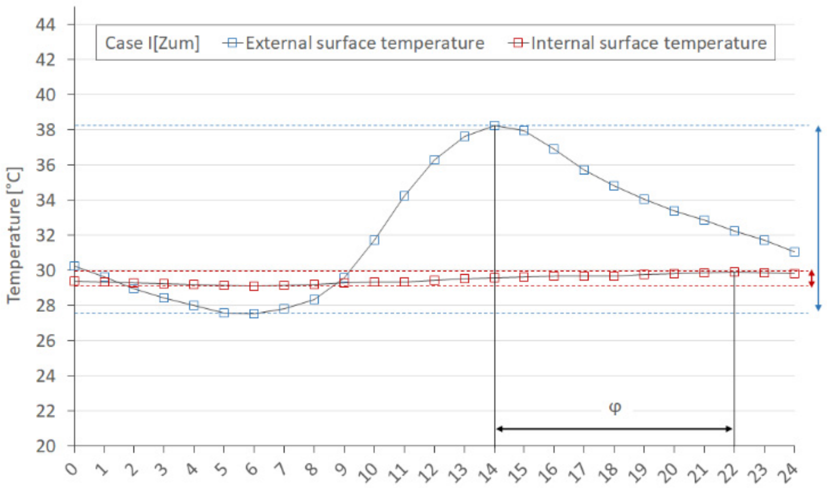


Figure 11. The fluctuation of the internal and external surface temperatures of the south wall of the case I[Zum] assessed on 31 July.

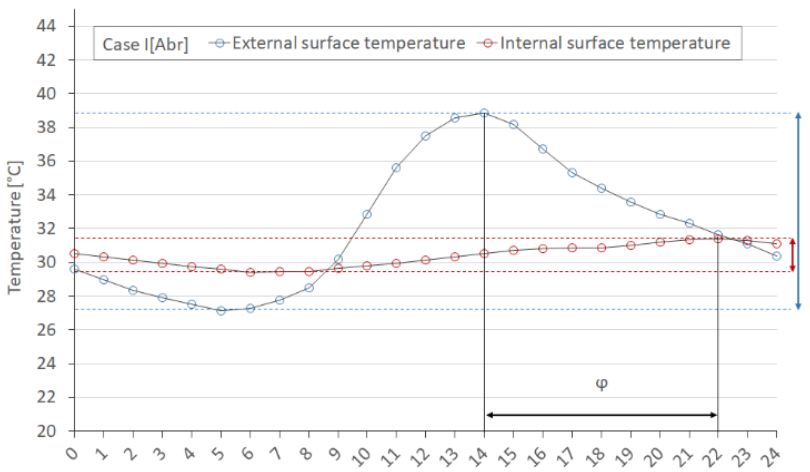


Figure 12. The fluctuation of the internal and external surface temperatures of the south wall of the case I[Abr] assessed on 31 July.

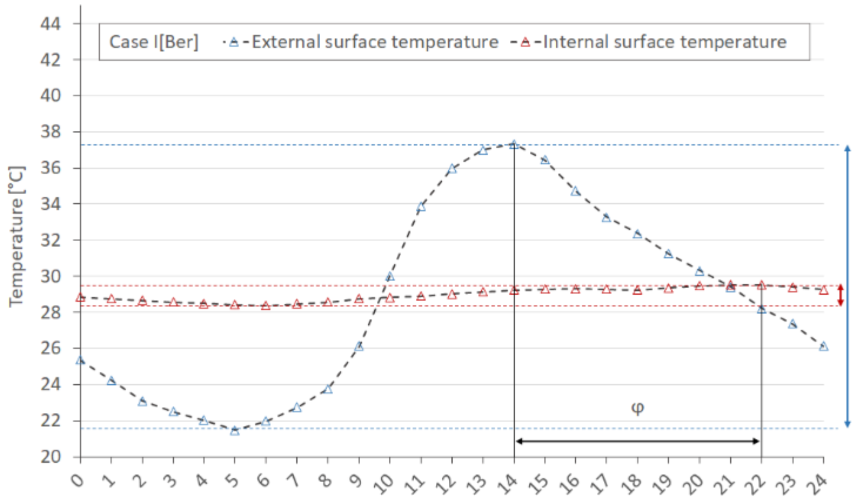


Figure 13. The fluctuation of the internal and external surface temperatures of the south wall of the case I[Ber] assessed on 31th.

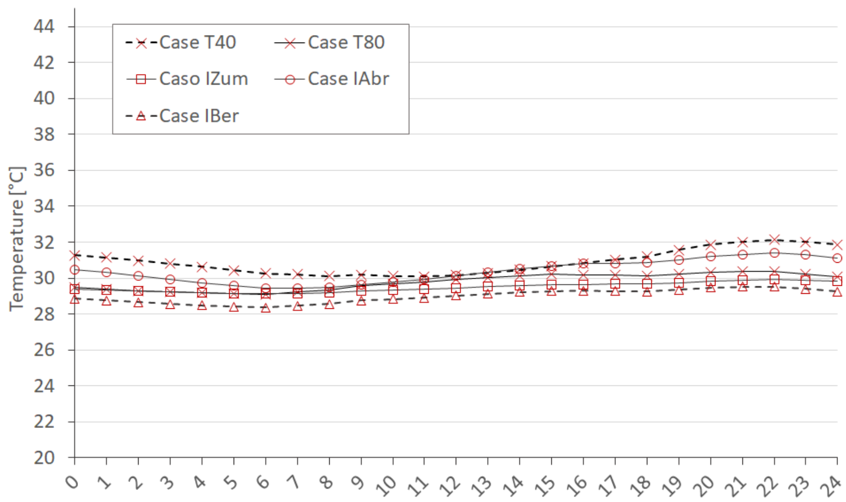


Figure 14. The fluctuations of the internal surface temperatures of the south walls of the five case studies.

The results obtained in the study of the surface temperature confirm the benefits of massive envelopes, which are able to delay the heat transmission and to dampen the outdoor thermal wave inside the building, keeping indoor temperatures more stable. In fact, as shown in Table 5, the maximum value of the internal surface temperatures for the traditional case studies is reached nine hours later than the maximum value of the external surface temperature while for the innovative case studies it is reached eight hours later. Moreover, the decrement factor, which was evaluated for the different case studies, ranges from 0.07 to 0.17 (Table 5). The highest value of the decrement factor is assessed for the case I[Abr] due to the inner position of the insulation layer.

Considering only cases T[40] and T[80], as the wall thickness increases, the decrement factor decreases, consistently with the results obtained by Asan [41]. However, the time lag does not change when masonry increases from 0.41 to 0.81 m, differently from the results obtained by the above mentioned work. The different outcome could be explained considering that the choice of EnergyPlus software to analyze high inertia-massive walls, may be considered not proper for walls with thicknesses larger than 0.60 m, as reported by Aste and colleagues [14]. Therefore, further analyses could be conducted, as future development, to more in depth investigate this point.

Table 5. The time lag (φ) and the decrement factor (f) assessed for the south walls of the five case studies, taking into consideration the maximum and the minimum values of the internal and external surface temperatures reached during the hottest day of the year (31 July).

Time Lag and Decrement Factor	Case T[40]	Case T[80]	Case I[Zum]	Case I[Abr]	Case I[Ber]
φ (h)	9	9	8	8	8
f (-)	0.12	0.08	0.08	0.17	0.07

3.3. Economic Analysis

Alongside with the architectural, technical and thermal energy performance, another important aspect when selecting an envelope system is the cost of construction of the selected solution, and the cost that are directly related to the envelope performance, such as the energy costs. Therefore, a brief economic analysis was performed. First, the cost of the different massive stone envelope systems were assessed; then, the cost of natural gas and electricity of the different case studies was evaluated. Finally, these two aspects were combined, in order to obtain an overall idea of each solution cost.

The approximate costs per square meter (€/m^2) for the external wall solutions used in the different case studies were estimated (Table 6) according to the unit costs collected in "*Tariffa dei prezzi 2012 Regione Lazio*". Furthermore, the total costs of the entire envelope for each case study were evaluated (Table 6), and the differences between the cost of the case T[40] and the costs of the cases T[80], I[Zum], I[Abr] and I[Ber] were assessed. The average cost per square meter of the traditional envelope systems of cases T[40] and T[80] is about 215 €/m^2 while the average cost per square meter of the innovative building solutions of cases I[Zum], I[Abr] and I[Ber] is about 296 €/m^2. The cost of the innovative envelope solutions is higher because it takes into account the additional costs related to the reinforced concrete/steel load-bearing structures and to the thermal insulation layers.

Table 6. Costs per square meter and total cost of the envelope solutions of the different case studies.

Construction Cost	Case T[40]	Case T[80]	Case I[Zum]	Case I[Abr]	Case I[Ber]
Cost per square meter [€/m^2]	159.1	271.1	316.8	332.8	239.2
Total cost [€]	34,114.1	58,127.5	67,921.5	71,347.7	51,285.8

The annual costs for heating and cooling were evaluated (Table 7) considering the unit costs of electricity and natural gas available on the website of the Italian Authority for Electric Energy Gas and Hydric Systems. Moreover, the annual savings with reference to the case T[40] were assessed: the annual savings for heating relative to innovative solutions (cases I[Zum], I[Abr], I[Ber]) are on average 213.6 €/year while the ones for cooling are on average only 38.4 €/year.

Table 7. Annual costs for heating and cooling.

Energy Cost	Case T[40]	Case T[80]	Case I[Zum]	Case I[Abr]	Case I[Ber]
Annual cost for heating [€]	421.5	426.1	209.5	219.6	194.6
Annual cost for cooling [€]	132.5	111.1	96.1	106.6	79.7

By considering the results of this economic analysis, it appears that more than 50 years are necessary to balance the higher construction cost of the innovative case studies when comparing them with the traditional solutions. However it has to be considered that the traditional case studies have an envelope system with a thermal transmittance, which is far higher than the limit value imposed by the Italian energy-saving regulations [4] and, therefore, a retrofit intervention such as the installation of a thermal insulation layer would be necessary. If the costs for the needed refurbishment were considered, the energy savings of the innovative case studies would balance their grater construction costs in a shorter period.

4. Conclusions

In this paper, a technical, thermal energy and economic analysis of selected innovative massive stone envelopes, which have been developed by the contemporary architectural culture in recent years, is presented. Stone constructions characterize the Italian architectural environment, especially in the numerous historical urban centers, which are diffused all along the national territory. Therefore, stone construction elements allowed the forging of a strong architectural identity, based on the locally available stone materials, which allowed also merging constructions with the surrounding natural environment. The resulting building culture should be promoted when building in historical areas developing new design approaches that (i) enhance its aesthetic and environmental potential, (ii) meet the energy-saving requirements and (iii) guarantee users' indoor thermal comfort and safety. Therefore innovative solutions that are able to express urban identity while still avoiding historicist approach, and that are also able to solve the issue related to traditional construction weaknesses, were here considered for these purposes.

The analysis of the state of the art and literature brought to the identification of three peculiar stone envelope technologies, which all have the characteristic to overcome performance weaknesses of single-layer stone masonry, and which allow the stone layer to be coupled with a concrete/steel structure, as well as with additional insulation layers. Vals thermal bath by Peter Zumthor, High Musical Studies School of Galicia by Antón García-Abril Ruiz and Haus 9 $\times$ 9 by Titus Bernhard were selected for this analysis, and their envelopes were studied and compared to traditional stone masonry envelopes in terms of technical solution and thermal energy performance. The analyses have shown that innovative envelopes are suitable also for building in historical areas, where it is of primary importance to adopt a landscape-compatible design approach, both in new constructions and in retrofit interventions.

The thermal energy performance of the analyzed contemporary envelopes were assessed and compared to the one of traditional stone masonry solutions, through dynamic simulations performed on a case study building, where the only variable was the envelope technology itself. The results of the simulations have shown that innovative massive stone envelopes ensure lower annual energy demand with respect to traditional ones, due to their lower thermal transmittance. Furthermore, they are able to delay heat gains throughout the opaque envelope and to dampen the outdoor thermal fluctuation inside the building. Thus, they keep indoor operative temperature more stable due to the high thermal inertia of the wall.

Finally, the implementation costs of the stone envelope building solutions were evaluated, as well as the energy consumption costs of the selected case studies, and the costs of innovative and traditional solutions were compared. The results of the economic analysis show that although the annual energy savings are significant, the high costs per square meter of the stone envelopes can be amortized only over a very long period of time. However, for the traditional case studies, a retrofit intervention to achieve the prescribed thermal transmittance should be added to the cost of the envelopes system, reducing the gap with the innovative ones.

Further investigation of the thermal energy performance of innovative building solutions through on-site measurement will represent a future perspective of this research in order to validate the results of the simulation. Moreover, the specific architectural features of different building typologies will be considered, since it could open interesting perspectives on the coupling of envelope technology and occupants' activities. Finally, since the effect of thermal inertia is inherently dependent on climatic conditions, in particular on outdoor air temperature and solar radiation [39], future development of this research will investigate it in a range of different climatic conditions.

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