Modelling, Measurement and Control B
Vol. 87, No. 3, September, 2018, pp. 135-142
Journal homepage: http://iieta.org/Journals/MMC/MMC_B

Energy efficiency improvements in historic buildings: Analysis of a case study in central Italy

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https://doi.org/10.18280/mmc_b.870304

Received: 6 March 2018
Accepted: 20 April 2018

Keywords:
energy efficiency, thermo-hygrometric comfort, historic buildings

ABSTRACT

The energy requalification strategies of buildings commonly involve the adoption of improvement interventions regarding the thermal features of the building envelope and the efficiency of the HVAC system. Furthermore, in historic buildings various architectonic, town planning and landscape constraints often reduce the number of solutions to be adopted.
The energy requirements prescribed by Italian legislation have recently been extended to historic public buildings too. Taking into account the indications of the current Italian law, the authors carried out an energy efficiency audit and upgrade of "Palazzo Valignani", an important architectural building located in Chieti, a small town in central Italy, currently under structural refurbishment due to the earthquake that hit the Abruzzo region in 2009.
The authors carried out an analysis in dynamic conditions using DesignBuilder software concerning the energy performance of the building with the aim to define the best energy efficiency improvements, by considering the thermal envelope performance, the HVAC system efficiency, the thermo-hygrometric comfort and the economic point of view. The results of this study show that, despite the architectural and historic restrictions, it is possible to achieve significant improvements in the energy efficiency of historic buildings in full compliance with current energy legislation in Italy.

1. INTRODUCTION

The European Directives on energy performance of buildings [1-2], underline the importance of reducing the energy consumption for heating, cooling, domestic hot water and electricity, particularly regarding public buildings [3]. They have been implemented in Italy by Law 90/2013 and recently the Italian legislation concerning the energy performance of buildings has been extended to historic buildings [4-5].

Therefore, as of that date, it is mandatory to calculate the energy performance index and draw up an energy certificate also for historic buildings.

For this purpose the AICARR (Italian Association for Air Conditioning, Heating and Refrigeration) has published the "Energy Efficiency in Historic Buildings" Guidelines that give useful information regarding methods for improving the energy performance of historic buildings by taking into account their architectonical value that imposes important restrictions [6-7].

Even ASHRAE has recently produced guidelines to be used as reference for all the energy improvement interventions on historic buildings [8-9].

The Italian housing stock has a great amount of historical buildings. As underlined in [10], about 12.5 million Italian buildings were constructed before 1945 and therefore can be defined "historic buildings". Since they are often characterized by features of high artistic level, they are protected by ministerial authorities. In many cases, particularly in minor towns, they are used as the site of public administration offices, museums or art galleries. This is common in Abruzzo, a region of central Italy, where we can find numerous small towns with buildings characterized by valuable historic and architectural features.

Starting from these considerations, it would be appropriate to adopt effective strategies to save energy in historic buildings. From this point of view, de Santoli et al. have shown that interventions on the building envelope are more efficient than improvements of the plants [11] both from an energy consumption and environmental point of view. This is confirmed by G. Dall'O' and L. Sarto that highlight that the energy retrofit of the building envelope is more convenient from an economic point of view than the energetic improvement of plants. [12]

In [13] the authors proposed a new approach for identifying more efficient energy improvement interventions in historic buildings, by illustrating the case of a small urban center in Abruzzo. The procedure used is based on an on-site investigation and the analysis of solutions able to assure a better energy performance of the building.

In addition, in [14] an experimental and numerical approach for the energy requalification of historic buildings was proposed, and the authors demonstrated that, despite the architectonic and historic restrictions, a significant reduction in energy consumption is possible through energy improvement interventions that have been accurately evaluated.

This is confirmed by Tadeu et al. that show that a significant energy saving can be achieved without changing the building's architectural features, taking into account the economic and environmental aspects. [15]

In this paper the authors chose to evaluate "Valignani

Palace", an important historic building located in Chieti (Abruzzo). It is currently under structural refurbishment, because the earthquake that took place in Abruzzo caused significant structural damage to many historic buildings and Valignani Palace is one of these.

The need to consolidate the damaged structures gives the opportunity to carry out energy improvements in compliance with the numerous architectonic restrictions.

In these situations, it is often the case that the energy requalification is carried out without a pre-evaluation of energy saving, economic and comfort aspects.

In this regard, the authors intend to demonstrate the usefulness of a calculation of the building's energy performance after each energy improvement intervention, through a dynamic thermal simulation, which allows to determine the best solution to be adopted.

In this paper they chose interventions compatible with the architectural features of the building and they then evaluated the energy saving amount of each one by DesignBuilder software.

2. DESCRIPTION OF THE BUILDING

The building under study is Valignani Palace, also known as Achille's Palace. It is located in Chieti, the oldest city of Abruzzo and one of the oldest in Italy. According to the citizens, it was founded 494 years earlier than Rome foundation.

The town is about 15 km distant from the Adriatic Sea and no more than 30 km from the beautiful mountains of Abruzzo. It is also a focal point of the life of the local population, along with nearby Pescara, with which it forms a real metropolitan system.

The building overlooks S. Giustino square, and it is located on the right side of the cathedral. It was built in 1517 and it was once used for residential purposes by the Valignani family. In the nineteenth century, the palace was the site of the episcopium, but since 1870 it has been the site of the Town Hall.

According to tradition, about two thousand years ago, in the area between the entrance of the current municipal building and the crypt of S. Giustino cathedral, there existed a pagan temple dedicated to Hercules.

In the atrium of the Town Hall, on the vault, there is the emblem of the city of Chieti with the hero Achille on horseback. The loggia is a remarkable testimony of the ancient Renaissance structure. In the courtyard there is a Roman column with the bronze horse of Achille upon its Corinthian capital.

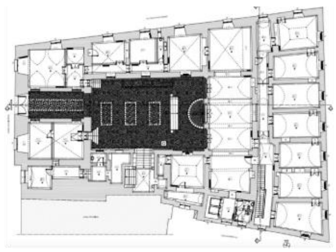
Presently it is the site of an archaeological collection and a picture gallery, which can be considered one of the most important art galleries in Abruzzo. Over the years the building has always maintained a good state of conservation.

The building suffered damage caused by the seismic event of April 2009, and from that day on, it was no longer used as a public building. In the days immediately following the earthquake, the building has been subjected to safety work, such as the use of underpinnings with metal structures and the installation of iron chains anchored to the bearing walls.

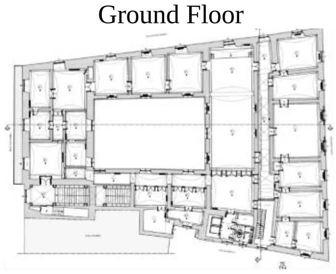
2.1 Architectural features of the Building

Valignani Palace is a four levels building: the ground floor with a net area of about 730.00 m2, the first floor of 807.00 m2, the second floor of 750.00 m2, the third floor of 430.00 m2, over a basement level intended for archives and commercial activities. Some pictures illustrating the building are shown in Figure 1, while Figure 2 shows the plant areas of the ground, first and second floors.

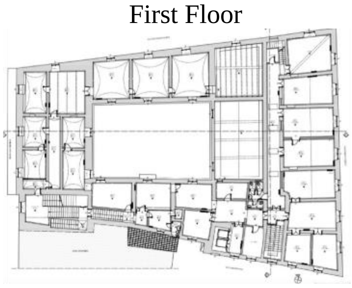
Figure 1. Views of the Palace



Ground Floor



First Floor



Second Floor

Figure 2. Main Planimetry of ground, first and second floors

2.2 Thermo-hygrometric features of the structures

The external vertical walls of the building are made of solid brick masonry. Regarding the roof, the original covers are made of wood with roughly rough-hewn trusses and double overlapping warping. They are pitched inclined with a cloak of tiles except for the slopes of the block in front of the square that have been left protected with only waterproof bituminous mantle, following the earthquake. The east portion of the building has a brick roof protected by a waterproof sheath and a tiled roof. In Table 1 the stratigraphy and dimensions of these structures are shown.

The external vertical walls have a thermal transmittance U of 0.95 W/m^2 K, higher than the value indicated by law of 0.36 W/m^{2}K, while the wood cover presents a U value of 2. 61 W/m^2 K and the value of law is 0.28 W/m^2 K. Finally, the masonry cover has a transmittance value of 1.12 W/m^2 K, higher than the value of law of 0.28 W/m^2 K.

Table 1. Stratigraphy of the main structures

		m
	Vertical external walls	
1	Plaster	0,02
2	Solid brick masonry	0,60
3	Plaster	0,02
	Wood cover	
1	Wood	0,025
2	Waterproof sheath	0,004
3	Tiled roof	0,004
	Brick and concrete cover	
1	Plaster	0,01
2	Concrete and masonry	0,20
3	Waterproof sheath	0,004
4	Tiled roof	0,01

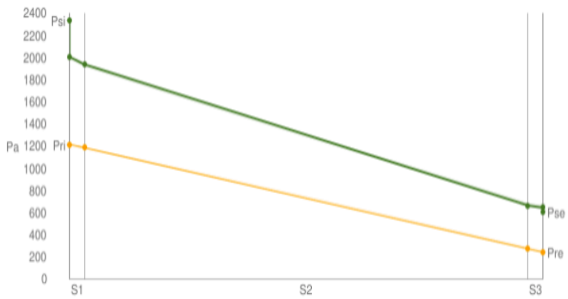


Figure 3. Diagram of Glaser for external walls

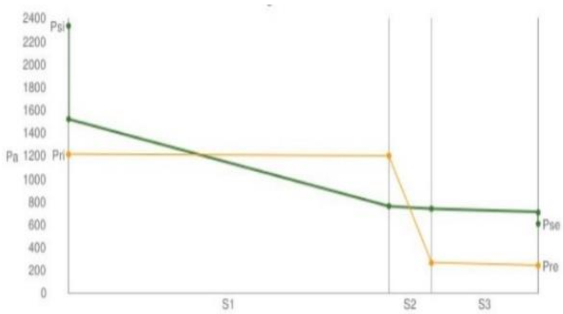


Figure 4. Diagram of Glaser for wood cover

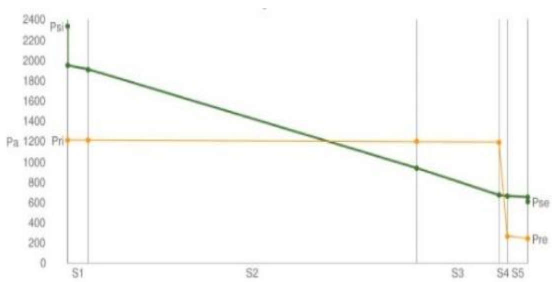


Figure 5. Diagram of Glaser for brick and concrete cover

Figure 3 highlights that the external walls are not subjected to condensation, while in Figures 4 and 5 it is evident that condensation takes place in the wood cover and in the masonry cover.

The fixtures were classified according to the transmittance values; five different typologies were identified. In Table 2 they are classified based on their thermal transmittance.

Table 2. Classification of existing openings

	Type	Frame	Material	Uw [W/m2K]
1	window	Wood	glass	4,9
2	window	Aluminum	glass	3,1
3	window	Wood	glass	5,0
4	showcase	Aluminum	glass	3,1
5	door	Wood	wood	2,1

3. METHOD OF ANALYSIS

The DesignBuilder software, equipped with the calculation engine Energy-plus, has been used to determine the building's energy performance. The three-dimensional model of the building has been designed by the software Autocad and Revit and exported in DesignBuilder. The building's energy performance in dynamic conditions have been calculated after setting its thermo-physical parameters and the external climatic conditions.

The building is located in Chieti, thermal zone D, 1556 Degree Days, the heating season going from November 1st to April 15th, according to Italian rules.

The HVAC systems have been analyzed by using the simple model option.

After analyzing the existing state of the building the authors propose some improvement interventions and evaluate the energy saving benefit for each one. In Figure 6 the three-dimensional models of the building are shown.

Real energy consumption data of Valignani Palace have been compared to data from DesignBuilder simulation in the considered climatic zone [16], in order to validate the simulation model. The annual energy consumption of the building of the five years preceding the 2009 earthquake have been taken into account, as shown in Figure 7.

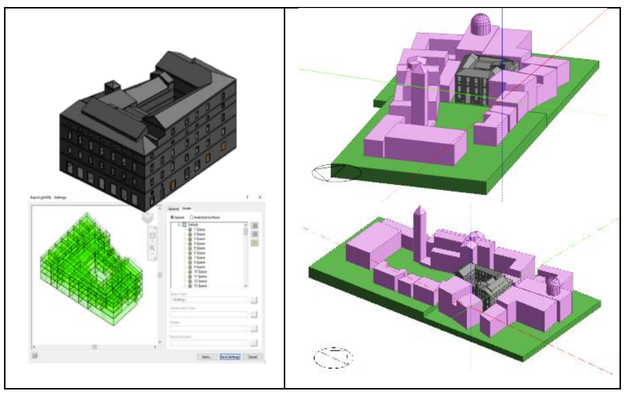


Figure 6. Three-dimensional models of the building

The average value of these has been considered to verify the implemented numerical model.

Data comparisons were carried out both on gas and electricity energy uses and a good agreement is verified, as shown in Table 3.

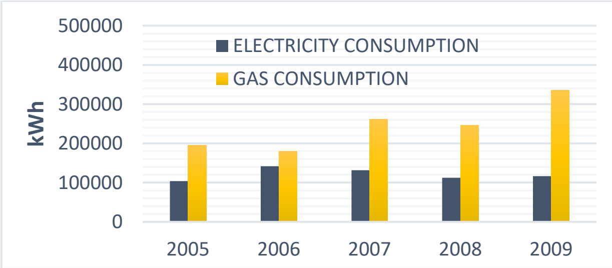


Figure 7. Annual Electricity and gas consumptions

Table 3. Comparison of energy consumption data

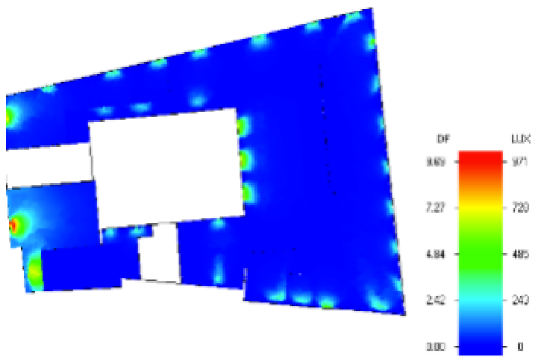
	Electricity [kWh]	Gas [kWh]
Real	121256.6	243566.0
DesignBuilder	115240.0	242467.8
Difference	4.96 %	0.45 %

3.1 Thermal analysis of the existing building

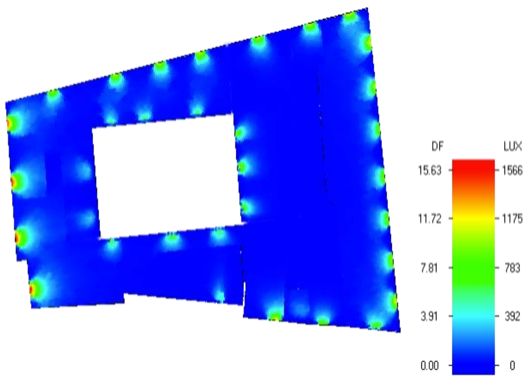
The dynamic simulation of the building enabled the researchers to determine the yearly heating demand which is about 57 kWh/m^{2}y and for domestic hot water which is about 5.6 kWh/m^{2}y, while electricity consumption is 29.8 kWh/m^{2}y. The summer conditioning demand is negligible.

Winter heat loss by air infiltrations through windows play an important role, underling the poor quality of the fixtures.
Starting from these considerations, it is evident that energy improvement interventions are necessary in winter conditions.

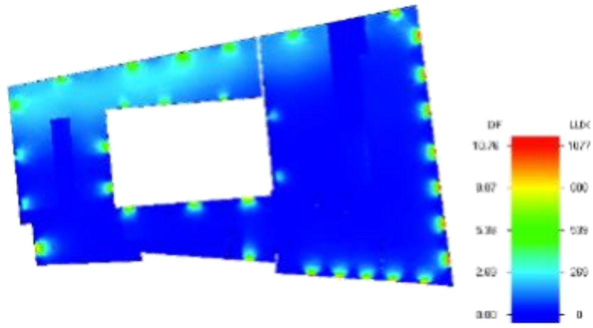
Furthermore, thanks to DesignBuilder software it was possible to determine the availability of daylight in interior environments, useful for guaranteeing the best visual comfort conditions for the occupants and a significant energy saving amount.



Ground floor



First floor



Second floor

Figure 8. Availability of daylight

The availability of natural light is limited, as shown in Figure 8, due to the compactness of the building, but also because numerous buildings are located around it. The surrounding buildings constitute obstructions that hinder the entry of natural light through the windows, therefore artificial lighting consumptions are consistent.
Based on the results of this analysis it would therefore be useful to improve the performance of the lighting system, specifically by modifying the lighting fixtures.

3.2 Energy improvement interventions

The first phase of the building's refurbishment regards an improvement of its static and seismic vulnerability and it is already in progress. This intervention has the priority to reduce the static and seismic weakness of the building, through the inclusion of floor chaining that will give greater stability to the load-bearing walls of the building, including local interventions such as the addition of architraves and targeted interventions with the aim of lightening the vaults.
In addition, the replacement of windows and some improving interventions on the walls and thermal system have been programmed. In particular,the current windows will be completely replaced with double glazing windows equipped with a frame of laminated pinewood from Sweden, having a thermal transmittance value of 1.4 W/m^2 K and the existing heating plant, consisting of a double traditional gas boiler equipped with cast iron radiators, will be substituted by multi-split air conditioners, known as VRV systems, that use variable refrigerant flow control to maintain individual zone control of each room of the building both in winter and summer condition.

Twelve outdoor units will be located in two technical areas in the attic room at the higher level of the building, provided with a suitable ventilation opening, in compliance with architectonic restrictions given by the Superintendence.
Besides, the authors examined the following different typologies of solutions for the new thermal plant.
The first alternative heating plant consists of aluminum radiators connected to a double condensing boiler.
Finally a floor heating system has been taken into account in two configurations: in the first it is connected to the condensing boilers and in the second to a heat pump system with a COP equal to 4.

The condensing boilers are less encumbrance than the existing gas traditional boilers, so no additional technical space is necessary, while the heating floor system can be installed because all the existing floors have been removed during structural refurbishment with the aim of lightening the vaults of the building.

All the considered configurations are compatible with architectonic restrictions and allowed by the Superintendence.

Furthermore, the authors examined the following additional energy improvement interventions and determined the energy saving of each one.

In particular, in order to optimize the artificial light performance, the fluorescent lamps presently installed will be replaced with 129 LED tube T8 60 cm (10 W, 1000 lm) and 391 LED tube T8 120 cm (20W, 2000 lm).

The termo-hygrometric features of the building's envelope will be improved. In this regard, the analysis carried out on the present configuration of the building shows that the vertical structures present transmittance values exceeding nearly three times those imposed by legislative regulations. Consequently, the authors propose to install a thermal insulant panel on the interior side of the walls. This is due to the fact that external insulation cladding is unauthorized, since the building is a historic building bounded by the architectural Superintendence restrictions. Thermal insulation installed inside the walls is typical procedure for facades of particular value, or facades that have particularities for which any intervention on the external side of the walls is not possible.

In this case the thermal insulating panel applied is a 60 mm thick polyurethane polyis foam, with Polytwin coatings on both sides, coupled to a 12.5 mm drywall slab. With the new configuration the external walls present a thermal transmittance value of 0.27 W/m^2 K, and no condensation phenomena occur as confirmed in Figure 9.

A 100 mm EPS sheet plus 40 mm ventilation chamber, coupled with 12 mm OSB panel was installed both on the wood and the brick-concrete covers under the tiles. This is a system for thermoventilation of civil and industrial roofs which, thanks to its configuration, ensures considerable advantages in terms of living comfort and ease of installation. With the new configuration the covers present a thermal transmittance value of 0.28 and 0.245 W/m^2 K respectively. This intervention solves the condensation phenomena, as shown in Figures 10 and 11.

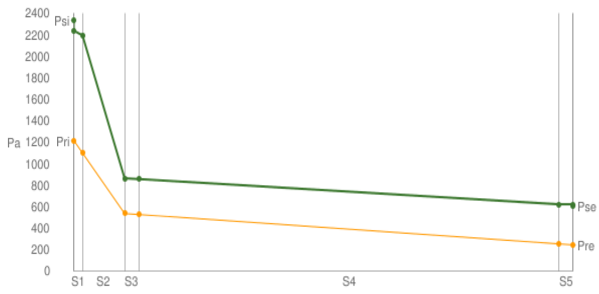


Figure 9. Diagram of Glaser of vertical walls

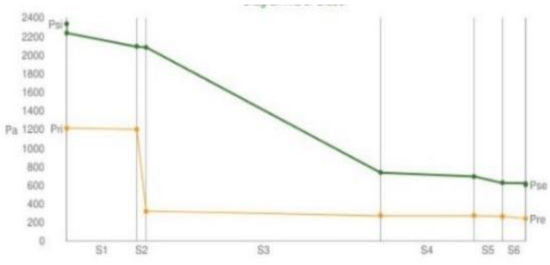


Figure 10. Diagram of Glaser for wood cover

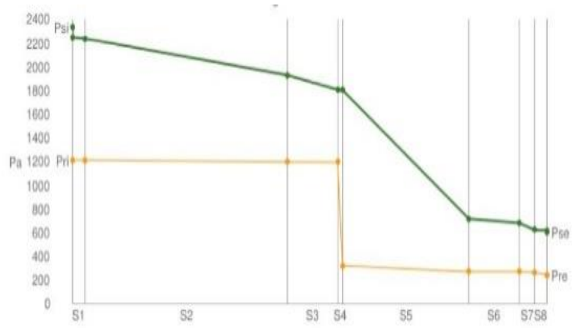


Figure 11. Diagram of Glaser for brick and concrete cover

Table 4 summarizes all the before and after configurations of the building for each intervention, and are defined by a progressive number.

Configurations 6, 7 and 8 do not include summer conditioning, being the summer conditioning demand unimportant, as confirmed by the thermal analysis of the existing building. Nevertheless in the east portion of the building some attic rooms with windows, are subjected to intense solar heat gains that cause overheating in summer condition.

To mitigate this effect, the authors proposed an additional intervention consisting in the installation of cool materials on the cover. The cool materials have the characteristic of reflecting solar radiation and re-emitting a certain quantity of absorbed heat. They are usually characterized by a very light color that is however not authorized for historic buildings in the Italian centers. A suitable solution could be represented by the use of materials with a cool color rendering.

Table 4. Configurations considered of the building

Conf. 1	Existing configuration
Conf. 2	Windows replaced + VRV system
Conf. 3	Windows and luminaires replaced + VRV system
Conf. 4	Windows and luminaires replaced, thermal insulation on vertical walls + VRV system
Conf. 5	Windows and luminaires replaced, thermal insulation on vertical walls and roofs + VRV system
Conf. 6	Windows and luminaires replaced, thermal insulation on vertical walls and roofs + aluminum radiators with condensing boiler
Conf. 7	Windows and luminaires replaced, thermal insulation on vertical walls and roofs + radiant panels with condensing boiler

They are based on pigments applied on a highly reflective substrate in the infrared spectral band. Since only the radiation that falls within the visible spectrum influences the chromatic feature of a surface, the cool colors would have the same visible appearance of traditional materials, but at the same time give a much higher solar reflectance. Starting from these considerations a tile with a similar color to that of the existing roof tile was chosen, in compliance with the requirements of the historic restrictions regulating the building.

In Figure 12 a picture of the chosen tile compared with the existing cover is shown. The chosen tile has a solar reflectance of 0.63 and a thermal emissivity of 0.83.

Through the installation of cool materials, a more comfortable thermo-hygrometric condition takes place in the attic rooms, as shown in Figures 13 which summarizes the temperature trend of a typical summer week (July 20th - July

27th). In fact, in the final configuration, after applying cool materials on the cover, both the external surface temperature and the interior air temperature are characterized by very low attenuation when compared to the corresponding trend of the current configuration.

Figure 12. The chosen tile and the existing cover

Furthermore, Figure 14 shows the PMV index in the attic rooms before and after the installation of cool materials during the same typical summer week. In the final configuration the PMV index is very close to the optimal value of 0 for the entire period.

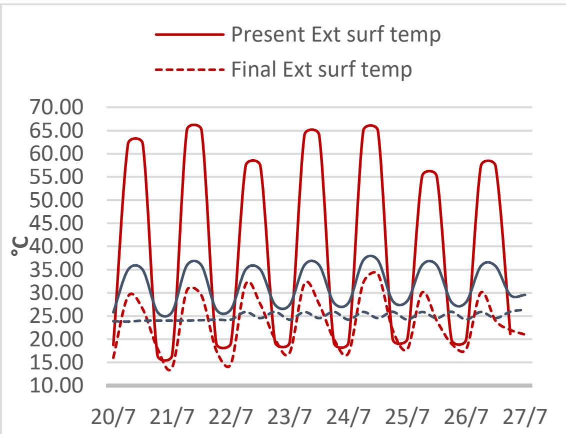


Figure 13. Temperature trend before and after cool material installation

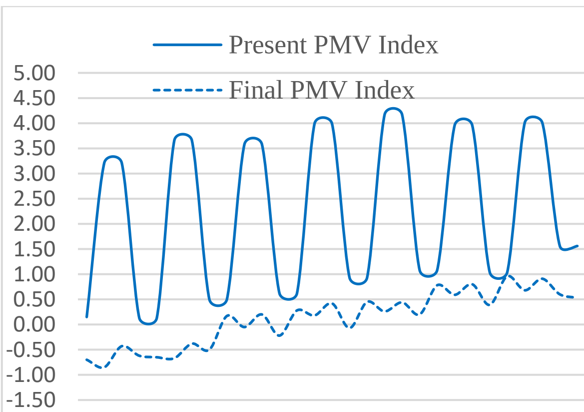


Figure 14. PMV index before and after cool material installation

4. RESULTS

The gas and electricity consumptions have been calculated for each configuration of the building. The results are shown respectively in Figures 15 and 16.

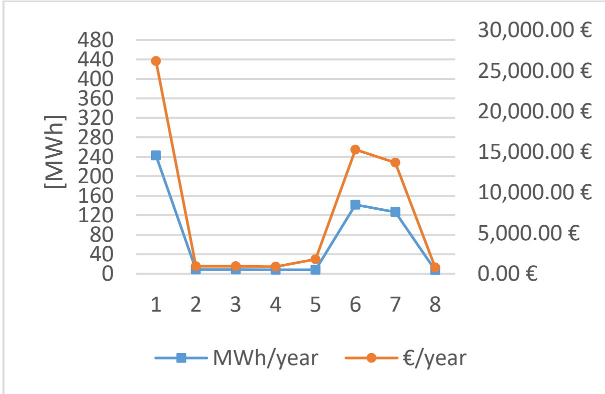


Figure 15. Annual gas consumption

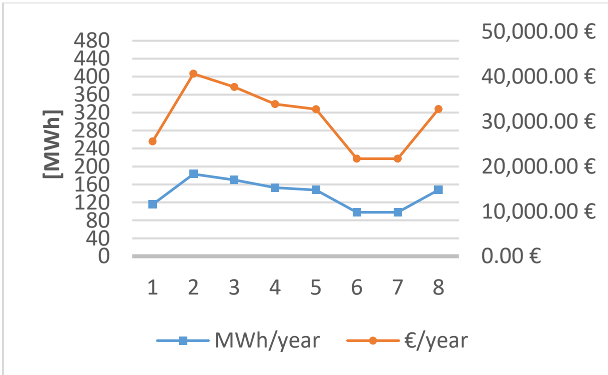


Figure 16. Annual electricity consumption

It is evident that all the considered interventions would result in a significant reduction of gas consumption. Configurations 2, 3, 4 and 5 have a very low gas consumption because the heating system uses electricity whose consumption, is, in fact, higher than configuration 1.

Obviously the electricity consumption is decreasing proceeding from configuration 2 to 5. It is about + 59% in configuration 2 with respect to the existing state of the building, + 47% in configuration 3, + 32% in configuration 4 and + 28% in configuration 5.

Configurations 6, 7 and 8 seem to be preferable from an energy saving point of view.

Configurations 6 and 7 allow respectively a gas consumption reduction of about 42 and 48 % and an electricity reduction of 15% in both cases if compared with configuration 1.

Finally, configuration 8 is characterized by a very small gas consumption (- 97%) and acceptable electricity consumption (+ 28 %).

4.1 Economic analysis

An analysis regarding a twenty-five yearlong economic budget was carried out in order to determine savings following future improving interventions [17].

Table 5, first column, shows net savings by taking into account the installation and maintenance costs and the tax contributions.

Table 5. Savings during the period of 25 years following interventions and amortizing period

	Savings (€)	Amortizing period (years)
1	/	/
2	341.457,80 €	/
3	437.053,25 €	6,2
4	566.435,07 €	13,2
5	598.225,13 €	13,2
6	487.069,13 €	13,4
7	540.556,61 €	13,4
8	597.644,19 €	10,5

The economic savings made it possible to evaluate the years needed to amortize the cost of the interventions, as shown in the second column of Table 5.

Configuration 3 seems to be preferable from this point of view, since it guarantees the shortest time to amortize costs. Also configuration 8 achieves an acceptable amortizing period.

4.2 Comfort indexes

The energy improving interventions will result more comfortable conditions from a thermo-hygrometric point of view. This is underlined by the results of the analysis regarding the PMV index, as shown in Figure 17. Both in winter and summer conditions, the PMV index is in the optimal range between -1 and 1. In particular, configurations 7 and 8 seem to give the best results.

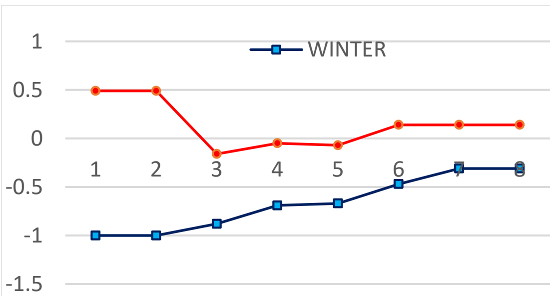


Figure 17. PMV index in winter and summer conditions

5. DISCUSSION

The results presented in the previous section show the efficacy of DesignBuilder analysis in order to determine the effects of energy improvement interventions on the building presented in this paper.

The authors considered eight different configurations of the building, taking into account both the thermal features of the building's envelope and the HVAC system. The first represents the existing configuration, the second that planned in the context of the structural refurbishment currently in progress, and the remaining ones are proposed by the authors.

The thermal analysis allowed to choose the more efficient solutions. Considering the high thermal inertia of external walls and taking into account that a new flooring must be built anyhow, the radiant floor system seems to be the most appropriate solution as it simultaneously ensures significant energy savings and a high degree of comfort.

In particular, configuration 7, with the radiant floor panel connected to condensing boilers, allows to achieve a significant energy saving amount, both in terms of gas and electricity consumption. Moreover it does not need more technical areas than existing ones. On the other hand it has an amortizing period longer than solution 8 that would be preferable from the economic point of view.

Anyhow, it is important to underline that the results of the software simulation permit to determine the best energy improvement solutions.

This consideration can be generalized. The authors think that a standard procedure of energy refurbishment of buildings should comprise a pre-evaluation of each energy improvement intervention.

This is particularly true in the case of historic buildings, where architectonic and landscape restrictions limit the feasible solutions.

6. CONCLUSIONS

This paper concerns the analysis of the energetic performance of the historic building named "Palazzo Valignani", located in Chieti, a small town in Abruzzo, damaged by an earthquake in 2009 and presently under structural restoration work.

The authors intended to demonstrate that significant energy improving interventions are possible in compliance with the restrictions regulating the architectonic value of the building.

They have proposed some energy saving interventions on the building envelope, the lighting and the heating plants by carrying out an analysis through DesignBuilder software with the aim of evaluating the energy saving benefits of each intervention, while taking into account economic aspects and thermo-hygrometric comfort indexes.

The results show that, despite the historical and architectural constraints, it is possible to realize effective energy saving interventions and achieve good results also from an economic and thermo-hygrometric comfort point of view.

Moreover, the authors demonstrated the usefulness of a pre-evaluation through a dynamic simulation of the building's thermal performance in the perspective of choosing the best energy improvement actions.

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NOMENCLATURE

U	ermal transmittance of walls $W .m^{-2}. K^{-1}$
U_w	ermal transmittance of windows $W .m^{-2}. K^{-1}$