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Article

Energy Retrofit Strategies for Residential Building Envelopes: An Italian Case Study of an Early-50s Building

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Abstract: During the last few years, the issues of energy efficiency and energy saving have dominated the buildings research field. New constructions are based on efficient design and, because of this, the real challenge is to retrofit existing buildings. Italian standards impose thermal transmittance limits for opaque and transparent surfaces, according to the climatic area. In order to understand buildings' energy behavior, an accurate analysis, carried out by employing advanced calculation codes and instrumental diagnosis—provided by the use of heat flow meter, surface temperature probes and thermal imaging camera—is needed. In this paper, a structure built in the 50 s has been analyzed, by means of a measurement campaign, to investigate the building's characteristics and its vulnerability. Finally, some retrofit hypotheses have been evaluated by means of a well-known dynamic code. All investments have to be analyzed under a financial point of view, considering materials and installation costs. For this reason, the payback time has been calculated in order to understand how quickly the energy upgrading can be repaid.

Keywords: buildings energy analysis; existing building retrofit; dynamic building simulation

1. Introduction

New buildings are based on efficient design and, because of this, in order to obtain an energy saving in the building sector, the real challenge is to retrofit existing constructions. Technical solutions have been characterized by an evolution over the years. For this reason, it is important to understand buildings energy behavior through accurate energy analysis [1–4]. Moreover, today it is possible to employ many software tools, based on advanced calculation codes, and perform instrumental diagnosis. It is well known that the building's component performances are important to define the annual energy consumption [5–13]. Wall performance depends on its thermal resistance, which is a measure of how well an envelope resists the heat-flow, and on the material heat capacity, which describes its thermal storage capability. Higher thermal resistance values allow us to obtain a better insulation and depend on thermal conductivity and thickness of each layer. In some conditions, the actual thermal resistance of building envelope components might not always agree with the value estimated during the design phase. Therefore, it is important to analyze the building envelope through *in situ* measurements by means of a non-destructive method that requires the use of a heat flow meter and a measurement time of at least 72 h [14]. It is important to remember that thermal transmittance measurements could be wrong if structural abnormalities are found in the measuring points. For this reason, a preliminary thermographic analysis is required to assess the correct application of the sensors, as shown, e.g., by Asdrubali *et al.* [15] that presented the results of a thermal transmittance measurement campaign performed for several building types. Moreover, the thermal imaging camera is very important to investigate the building's characteristics and its vulnerability. In their study, De Lieto Vollaro *et al.* [16] used a thermal imaging camera to analyze the envelope of an old building, detecting some badly-covered holes. The instrumental diagnosis is an important step to investigate the building's envelope and recreate a model able to represent the real structure behavior.

Moreover, the choice of an appropriate calculation code is important during the energy analysis [17]: building energy demands values obtained by means of semi-stationary software and dynamic ones can provide different results. For this reason, in their studies, Evangelisti *et al.* [18] and De Lieto Vollaro *et al.* [19] compared two models in order to analyze the energy performance of different buildings, one of them based on a simplified approach and the other one based on a time-dependent method, concluding for the critical importance of employing accurate dynamic analysis tools.

In particular, this paper is related to the theme of the redevelopment of social housing built in the postwar period, which was already addressed in the mid-1980s in countries like France and Germany. This social housing was characterized by extensive government interventions for meeting the housing demand. The rapid physical deterioration of this heritage building led to government interventions aimed at architectural, structural and energetic upgrading.

This study deals with the theme of the redevelopment of social housing through the thermal behavior analysis of an early-1950s building, by means of an instrumental diagnosis, based on heat flow meter and thermal imaging camera measurements. Starting from these data, a calibrated building model has been created and dynamic simulations have been performed to evaluate the influence of different retrofit measures on the resulting annual energy demands. It is well known that all the investments have to be investigated under a financial point of view, by taking into account materials and installation costs. Because of this, the payback time has been evaluated in order to assess how quickly the energy upgrading can be repaid.

2. Methodology

Buildings energy retrofit analysis requires simulation models able to reproduce the structure thermal behavior. It is well known that, in order to build these models, a dynamic software such as TRNSYS (Transient System Simulation Tool) [20] is needed. This software is based on an advanced calculation code, which applies the transfer function approach of Mitalas [21]. It has been widely demonstrated that, using this software, it is possible to properly reproduce the building geometry and the external environmental conditions. TRNSYS Build allows recreating the building model, and the external environmental conditions are applied by using TRNSYS Studio [22–24]. In this study, the weather conditions of the year 2014 have been reproduced through a TRNSYS Studio specific type, being the types small program codes written in FORTRAN or C++. The dynamic software is able to provide the thermal loads for each hour during the day. Building's characteristics can be deduced by visual inspections and *in situ* measurements, through the use of heat flow meter, temperature probes and a thermal imaging camera. The heat flow meter allows estimating walls thermal transmittance, the temperature probes are employed to measure air temperature inside the construction and thermal imaging camera allows analyzing the building envelope, in order to assess heat losses. Instrumental measurements are important to obtain a calibrated model. The calibration process is based on two index calculations: the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Squared Error (CV_{RMSE}) [25], defined as:

$$MBE(\%) = \frac{\sum_{i=1}^{Np}(m_i - s_i)}{\sum_{i=1}^{Np}(m_i)} \tag{1}$$

$$CV_{RMSE}(\%) = \frac{\sqrt{\left(\sum_{i=1}^{Np}(m_i - s_i)^2 \middle/ Np\right)}}{\overline{m}} \tag{2}$$

where m_i and s_i are respectively measured and simulated data values for each model instance i; N_p is the number of data points at interval p and $\overline{m}$ is the average of the measured data values. Currently, building energy simulation models are defined as calibrated if they meet the criteria set out by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Guideline 14 (MBE hourly criteria up to 10% and CV_{RMSE} hourly criteria up to 30%) [26]. After calibrating the model, it is possible to use it for the simulation of retrofit strategies, in order to improve the building's thermal performance and reduce annual energy needs. Figure 1 shows a scheme of the approach employed to address the retrofit design.

Figure 1. Schematic approach for the retrofit design.

All investments have to be analyzed under a financial point of view, considering materials and installation costs. Just to exemplify such financial considerations, we focus here on the retrofit based on the addition of an external coating of expanded polystyrene and we calculate how quickly the energy upgrading will be repaid. The ratio between the starting investment and the annual savings due to the additional thermal insulation is defined as payback time (PBT) and can be expressed as follows:

$$PBT = \frac{C_i \times R_{ante} \times R_{post} \times E}{C_e \times (R_{post} - R_{ante}) \times 24 \times HDD} \quad (3)$$

where C_i is the material installation cost, R_{ante} is the thermal resistance before the retrofit, R_{post} is the thermal resistance after the retrofit, E is the heating system efficiency, C_e is the energy cost and DD are the climatic zone heating degree days [27].

3. The Case Study

3.1. Building Characteristics

The proposed case study is represented by a construction built in Rome during the 1950s, belonging to a neighborhood placed in a central area of the city characterized by ten identical buildings and sixteen structures built in the same period. Figures 2 and 3 show its particular geometry, characterized by a star shape. The building presents a stairwell located in the center of the structure with the residential units organized all around. Table 1 shows the main information about the building geometry and geographical position. The vertical walls are characterized by an external layer made of concrete and an internal layer made of hollow bricks. The walls are plastered on both sides. The building doesn't have any basement.

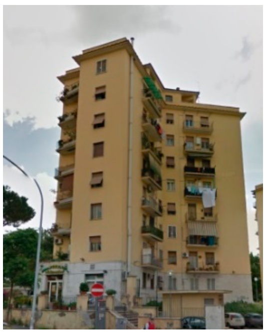
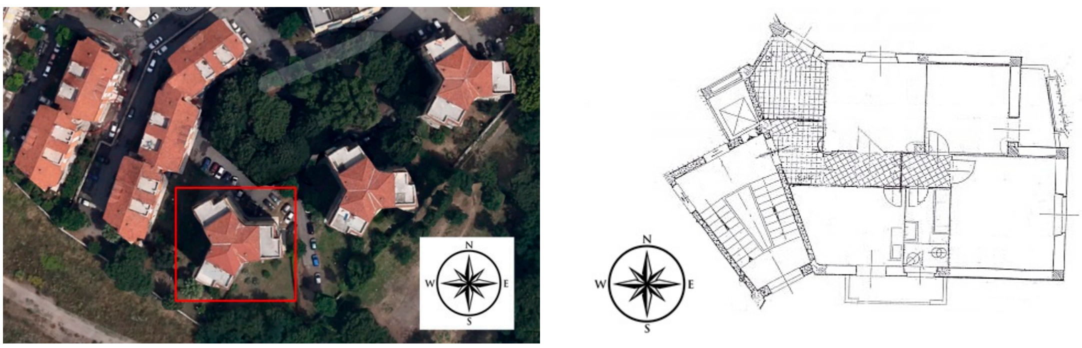


Figure 2. The case study.



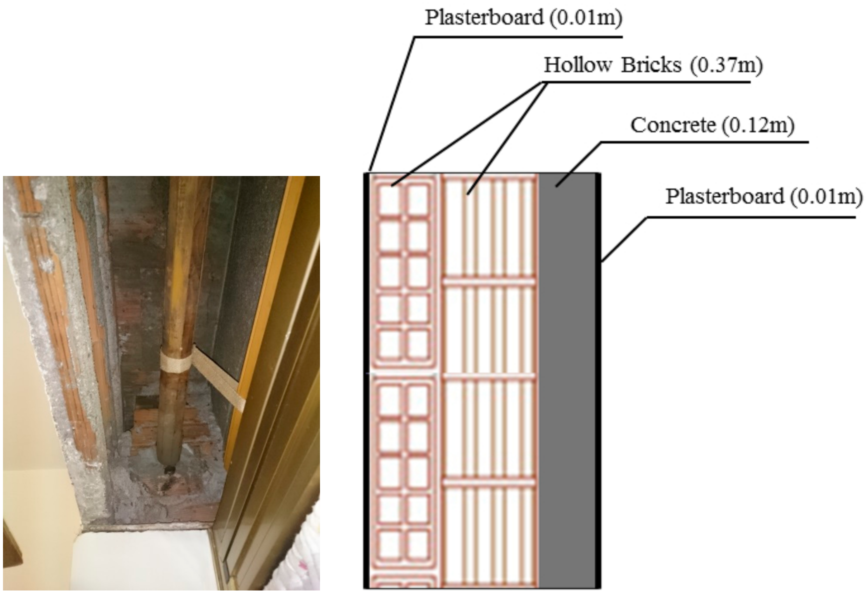
(**a**) (**b**)

Figure 3. (**a**) The analyzed building and its orientation; (**b**) Residential unit plan.

Table 1. Building characteristics and geographical position.

Building's characteristics	Values
Building Volume [m^3]	6984
Building Total Surface [m^2]	2948.4
Surface-Volume ratio	0.42
Opaque Surface Area [m^2]	2594.16
Transparent Surface Area [m^2]	354.24
Residential Units	24
Climatic Zone	D
Latitude	41°54′39″24 N
Longitude	12°28′54″48 E

Wall characteristics have been deduced by visual inspections of the bins containing the shutters, as shown in Figure 4. Despite this, assuming visual inspections not sufficient to understand the actual walls stratigraphy (and consequently not sufficient to estimate its thermal transmittance), *in situ* measurements of the wall thermal transmittance have been conducted by using a heat flow meter [28]. The instrument is provided with two temperature sensors: a plate that has to be applied on the inner side of the wall and an external wireless temperature probe. The heat flow meter proper operation requires the absence of thermal bridges. For this reason, a thermographic investigation has been carried out inside a residential unit (Figure 5).



(**a**) (**b**)

Figure 4. (**a**) Visual inspections of the bins containing the shutters; (**b**) Wall stratigraphy.

In agreement with to the Standard ISO 9869, measurement time has been chosen equal to 10 days (from 13 December until 23 December) according to the needs of some residents that have kindly allowed performing the measurement campaign in their apartments. The heat flow plate and the external temperature probes have been applied on a north-facing wall, in order to avoid the direct solar radiation. The measured thermal transmittance value is equal to 0.918 W/m^{2}K. As a result of the visual inspection and of the transmittance measurement, the walls, roof and windows main characteristics have been deduced and they are listed in Tables 2–4.

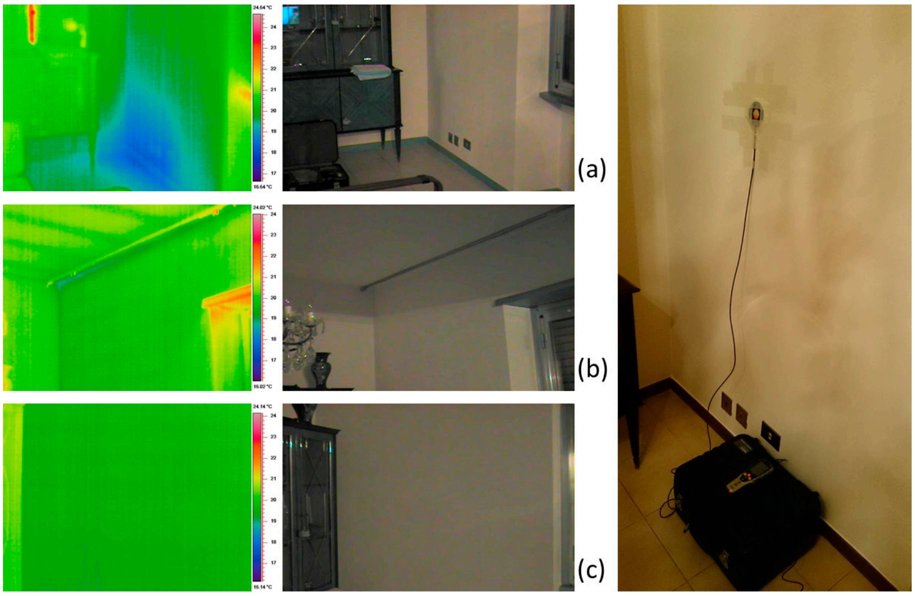


Figure 5. (**a**–**c**) Preliminary thermographic and visual investigation of the tested wall; (**d**) *In situ* heat flow meter measurements.

Table 2. Walls stratigraphy.

	Thermal Conductivity [W/mK]	Specific Heat Capacity [J/kgK]	Mass Density [kg/m³]	Thickness [m]
Internal side				
Plasterboard	0.350	840	1000	0.010
Hollow Bricks	0.589	840	700	0.370
Concrete	0.510	1000	1500	0.120
Plasterboard	0.350	840	1000	0.010
External side				
			Total Thickness	**0.51**
			U-value	**0.918 W/m²K**

Table 3. Roof stratigraphy.

	Thermal Conductivity [W/mK]	Specific Heat Capacity [J/kgK]	Mass Density [kg/m³]	Thickness [m]
Internal side				
Plasterboard	0.350	840	1000	0.010
Hollow Bricks	0.589	840	700	0.240
Cement Mortar	1.250	1700	2000	0.050
Waterproof Membrane	0.220	840	343	0.005
Cement Mortar	1.250	1700	2000	0.050
External side				
			Total Thickness	**0.355**
			U-value	**1.411 W/m²K**

Table 4. Windows characteristics.

	Thermal Transmittance [W/m²K]	g-value
Frame	2.27	-
Single Glass 4 mm	5.38	0.855

Moreover, as it is shown in Figure 6, in order to locate the heat losses sources, a thermal imaging analysis has been carried out also for the building envelope. As it can be seen, the building bearing structure is quite clear indicating that building insulation is not very effective.

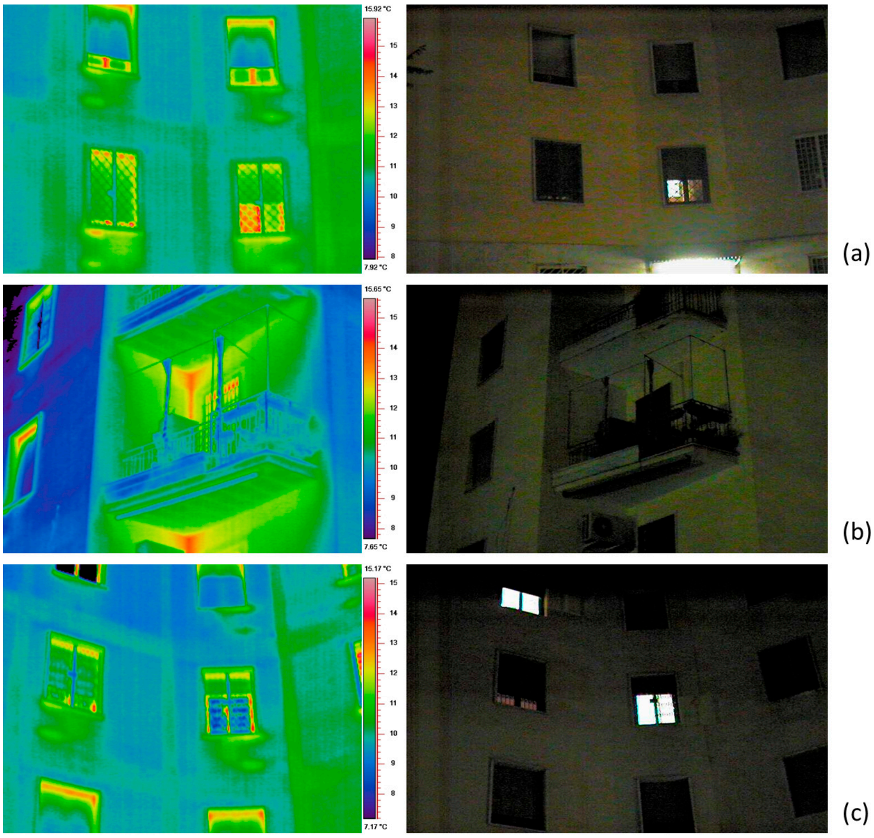


Figure 6. Thermographic (**left**) and gray-scale image (**right**) of the building envelope.

3.2. Building Modeling

The dynamic software TRNSYS has been used to create a model of the real building. In order to simulate the building energy demands, not having reliable information about the real plant, an ideal air conditioning system characterized by infinite power and different set-point temperatures was considered: the set-point temperatures are equal to 26 °C for cooling and 20 °C for heating [29]. The air conditioning system has been considered 24 h working. Taking into account some interviews conducted with some residents, an average number of two persons, always present, has been considered in the model. Moreover, ventilation rates have been set equal to 0.3 1/h. Solar shading devices have not been modeled.

According to the measured thermal transmittance value (U-value equal to 0.918 W/m²K) and to the visual inspections, the wall's stratigraphy has been built using the software. Moreover, the 2014 weather data for Rome have been collected (files acquired by the Roma TRE University weather station) and used as input and the model has been calibrated using the results of temperature measurements inside an apartment. Analyzing measured and simulated temperatures, the MBE and the CV_{RMSE} have been calculated. The MBE takes a value equal to 4.8% and the CV_{RMSE} is equal to 6%.

Table 5 lists the dynamic thermal performance of vertical and horizontal opaque surfaces.

Table 5. Walls and roof dynamic thermal performance.

Walls	
Surface mass	439 kg/m^2
Dynamic thermal transmittance	0.157 W/m^{2}K
Thermal attenuation	0.172
Thermal lag	12.86 h
Roof	
Surface mass	369.7 kg/m^2
Dynamic thermal transmittance	0.507 W/m^{2}K
Thermal attenuation	0.344
Thermal lag	9.29 h

The monitoring campaigns have been conducted throughout the season, acquiring data by means of different brief measurements (48 h), taking into account the person/apartment availability. Figure 7 shows the comparison between simulated and measured temperatures, considering only one of the several conducted measurement campaigns.

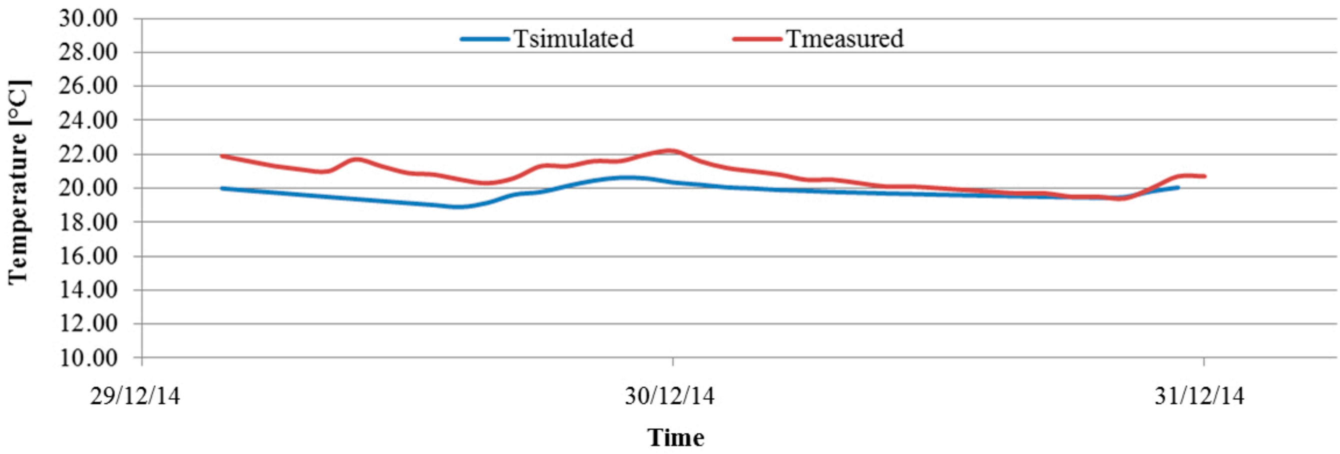
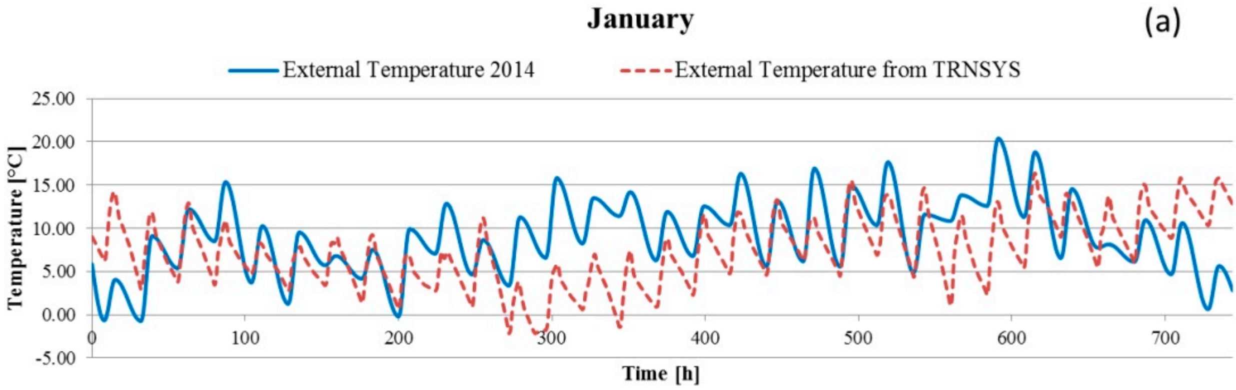


Figure 7. Comparison between simulated and measured temperatures.

Figure 8 shows the comparison between the modeled weather conditions for the 2014 and the TRNSYS weather-data. As shown, analyzing environmental temperatures during January and August supplied by the software and comparing them with the same months of the 2014, it is possible to observe that TRNSYS original weather-data are rather different during the winter, but they are very similar during the summer. This comparison has been done in order to verify the consistency between TRNSYS weather-data and the measured ones. The year 2014 was characterized by mild winter temperatures. Slightly different results could be obtained using TRNSYS weather-data, but the small discrepancy observed would not alter the overall conclusions of this work.

Starting from the analysis of the original building (the so called "base case"), different retrofit strategies have been simulated in order to understand the building's thermal behavior.



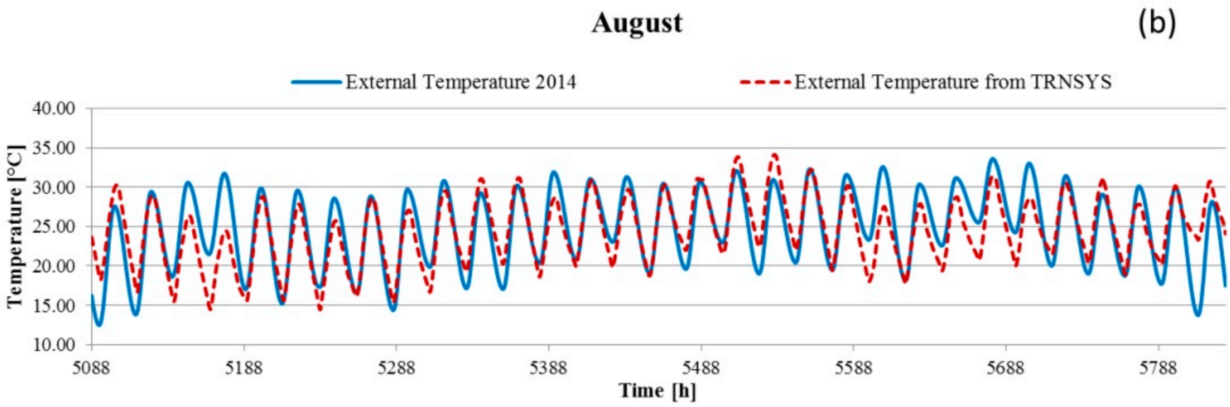


Figure 8. (**a**) Environmental temperatures in January; (**b**) Environmental temperatures in August.

3.3 Retrofit Strategies

In order to carry out the building envelope refurbishment, some possible interventions have been considered. Starting from the so-called "base case", three different types of windows have been tested, as can be seen in Table 6.

Table 6. Windows tested through the model.

	Structure [mm]	Thermal Transmittance [W/m²K]	g-value	Thermal Transmittance Limit (Climatic Zone D)
Frame	-	2.27	-	-
Double Glaze-AIR	4/16/4	2.83	0.755	×
Double Glaze-ARGON	4/16/4	1.40	0.589	√
Double Glaze-AIR (Low g)	6/16/4	2.54	0.440	×

These transparent surfaces have been simulated in the building thermal zones, in order to investigate their effect on the annual energy demands. Furthermore, to overcome the poor building insulation highlighted in Figure 6, the possibility of an external insulation based on a coating made of expanded polystyrene has been taken into account. This insulating material is characterized by a thermal conductivity equal to 0.040 W/mK, a specific heat capacity equal to 1.470 kJ/kgK and a mass density equal to 25 kg/m^3. Several thicknesses of the external coating have been tested ranging from 2 cm to 10 cm. As a further step, the horizontal surfaces have been insulated with an expanded polystyrene layer equal to 13 cm, located between the cement mortar and the waterproof membrane. The new thermal transmittance values are listed in Table 7. A 10 cm-thick vertical coating and a roof insulation with an expanded polystyrene layer characterized by a thickness equal to 13 cm, ensure compliance with the thermal transmittance limits (climatic zone D), according to the Italian standard [30]. Table 8 lists the walls and roof dynamic thermal performance after retrofit.

Table 7. Thermal transmittance values after retrofit.

Element	Thermal Transmittance [W/m^{2}K]	Thermal Transmittance Limit (Climatic Zone D)
Insulated Roof – EPS 13 cm	0.253	√
Wall - Coating 2 cm	0.629	×
Wall - Coating 4 cm	0.478	×
Wall - Coating 6 cm	0.386	×
Wall – Coating 8 cm	0.324	×
Wall – Coating 10 cm	0.278	√

Table 8. Walls and roof dynamic thermal performance after the refurbishment.

	Base Case Walls	Wall-Coating 2 cm	Wall-Coating 4 cm	Wall-Coating 6 cm	Wall-Coating 8 cm	Wall-Coating 10 cm
Surface mass	439 kg/m^2	439.5 kg/m^2	440 kg/m^2	440.5 kg/m^2	441 kg/m^2	441.5 kg/m^2
Dynamic thermal transmittance	0.157 W/m^{2}K	0.044 W/m^{2}K	0.025 W/m^{2}K	0.018 W/m^{2}K	0.013 W/m^{2}K	0.011 W/m^{2}K
Thermal attenuation	0.172	0.070	0.052	0.045	0.042	0.039
Thermal lag	12.86 h	14.41 h	14.71 h	14.9 h	15.08 h	15.28 h
	Base Case Roof	**Roof-13 cm EPS**				
Surface mass	369.7 kg/m^2	372.9 kg/m^2				
Dynamic thermal transmittance	0.507 W/m^{2}K	0.022 W/m^{2}K				
Thermal attenuation	0.344	0.085				
Thermal lag	9.29 h	12.69 h				

4. Results and Discussion

4.1. Retrofit Evaluation through Dynamic Simulations

In order to appreciate the transparent surface influence on the annual energy demands, the elements listed in Table 6 have been tested. The results shown in Figure 9, concerning the whole building, allow highlighting the simultaneous effects of varying thermal transmittance and solar gain factor (g-value). By progressively increasing insulation from the "ante operam" (single glaze) configuration, it is possible to obtain heating demand reductions of −40% (double glaze air) or −47% (double glaze argon). On the other hand, the window solar gain factor plays a fundamental role during the summer: Figure 9 shows that the cooling demand reduction reaches a value equal to −40% by using a solar control glaze. In this case, the solar control glaze, represented by the double pane 6/16/4 with air, allows almost halving the cooling energy demand and, at the same time, it is effective during the winter. Its thermal transmittance is higher than the one provided by the double glaze with argon (see Table 6) but, despite this, it allows reducing the heating energy demand (−31%) compared with the ante operam situation.

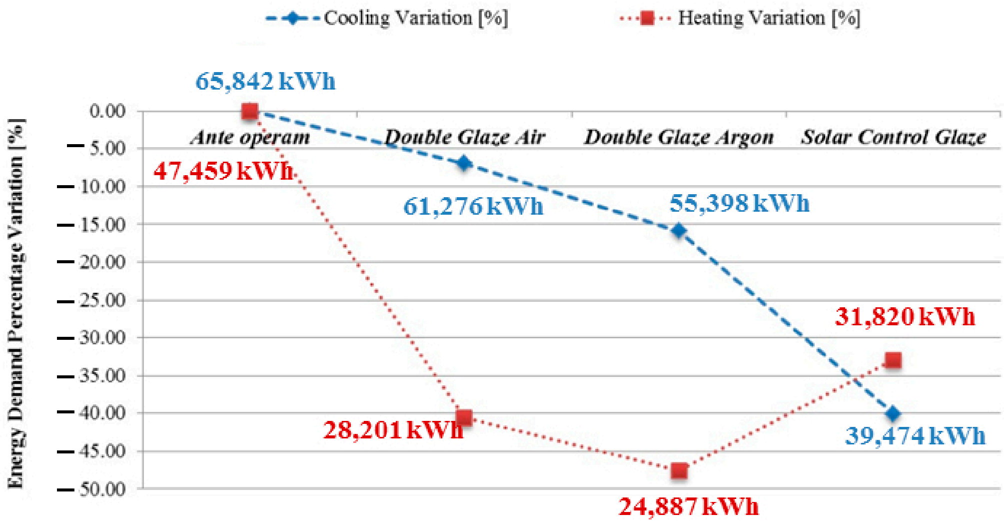


Figure 9. Energy needs percentage variations as a function of different transparent surfaces.

In order to investigate the opaque surfaces influence on the annual energy demands, the addition of an external insulation layer, consisting of an expanded polystyrene coating, has been simulated. A progressively increased thickness of the external coating, with a resulting reduction of the overall thermal transmittance, has been considered. It turns out that it is necessary to employ at least a 10 cm-thick insulation layer to comply with the thermal transmittance limit imposed by the Italian Standards (thermal transmittance limits, for the climatic zone D, are 0.290 W/m^{2}K for vertical opaque surfaces and 0.260 W/m^{2}K for horizontal ones). Eight types of possible interventions, whose details are reported in Table 9, have been compared. The results are reported in Figure 10.

Table 9. Description of the interventions.

Name	Description
Ante Operam	Base case
Int. 1	Insulated Roof—EPS 13 cm
Int. 2	Wall—Coating 2 cm
Int. 3	Wall—Coating 4 cm
Int. 4	Wall—Coating 6 cm
Int. 5	Wall—Coating 8 cm
Int. 6	Wall—Coating 10 cm
Int. 7	Wall (Coating 10 cm) + Roof (EPS 13 cm)
Final Retrofit	Wall (Coating 10 cm) + Roof (EPS 13 cm) + Double glaze with air (low g)

Intervention 7 represents the best solution to mitigate the wintry heat dispersions with an energy demand reduction of about 78%. At the same time the cooling energy demand increases of about 45%. This happens because, during the summer nights, when the outer temperature decreases below the inner temperature, a higher insulation limits the heat transfer to the outside. For this reason, the Intervention 7 and the solar control glaze employment have been concurrently simulated to reduce also the cooling demand. Using a Double glaze with air (low g) allows obtaining a heating demand reduction equal to −98% and a cooling energy increase limited to 1% (see Figure 9, Final Retrofit).

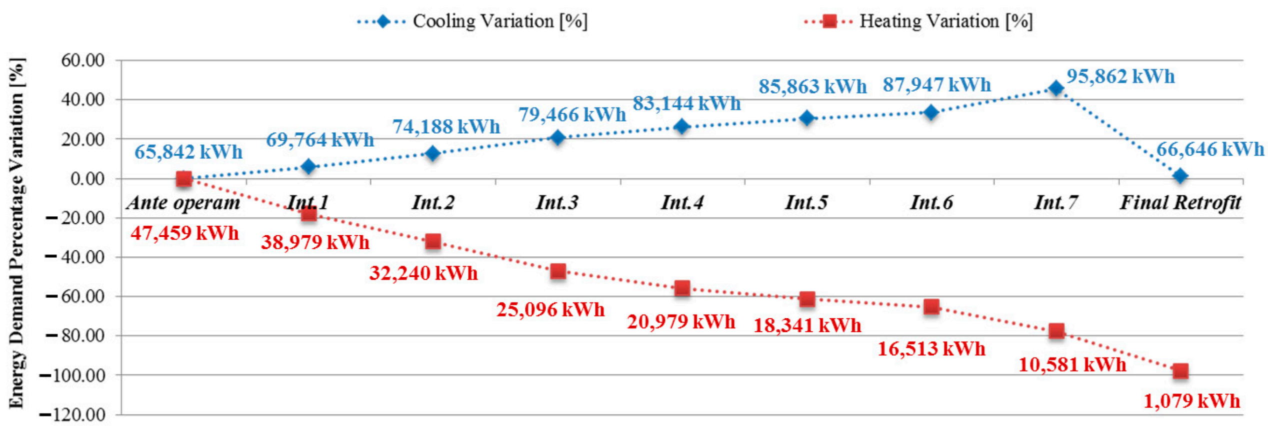


Figure 10. Effect of the opaque surface insulation.

It is worth stressing, in conclusion, that a higher envelope insulation does not represent the best way to optimize the building behavior during summer [31]. However, in the overall yearly energy balance, such retrofit measure can still prove beneficial if it is taken together with a proper way to limit the summer temperature increase arising from solar contribution, as obtainable with a low g-value glass.

4.2. Payback Time

In this case study, the material installation cost is approximately equal to 60 €/m^2 and the heating plant is more than 20 years old, so the system efficiency can be considered equal to 0.6. Moreover, the energy cost is equal to 0.0866 €/kWh (taking into account natural gas) and the building is placed in Rome (climatic zone D) with 1415 degree days. Figure 11 shows the payback time values as a function of the Expanded Polystyrene (EPS) thickness.

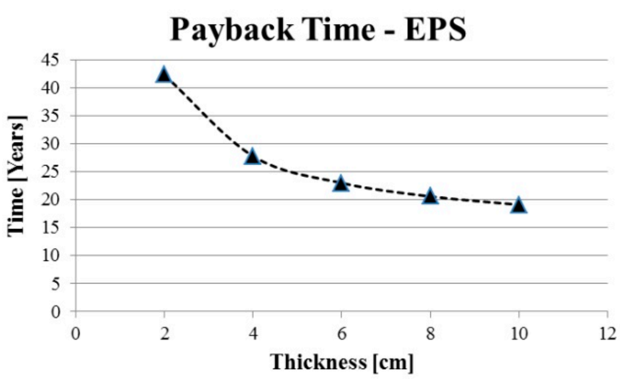


Figure 11. Payback times as a function of the EPS thickness.

Equation (3) shows that the payback time is a function of the wall's thermal resistance before and after the retrofit, without considering materials properties. Taking into account different insulation materials, it is possible to calculate payback times dependent on the material unit costs. There are a lot of insulating solutions, such as glass fiber panels, rock fiber panels, wood fiber panels or natural cork fiber panels. Setting R_{ante} equal to 1 m^{2}K/W and E equal to 0.6, considering a material installation cost that ranges from 30 €/m^2 to 60 €/m^2, the payback time as a function of material thickness and of its installation cost has been calculated. The result is reported in Figure 12 and shows that the payback time can be reduced to less than 10 years with a proper combination of cost and thickness of the insulating material.

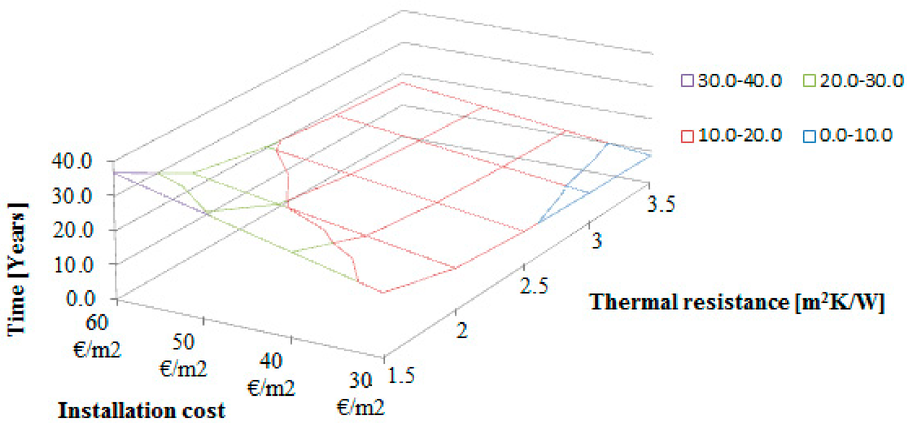


Figure 12. Payback time considering different installation costs and thermal resistances after retrofit.

5. Conclusions

In this paper, an early-50s building has been analyzed, conducting a measurement campaign to investigate the building's characteristics and its vulnerability. After that, some retrofit alternatives have been simulated and compared by means of a calibrated model.

Regarding transparent surfaces, three different windows have been tested. The results show that a higher thermal insulation allows obtaining the best heating demand reductions, but the window solar gain factor plays a fundamental role during summer. Indeed, a solar control glaze allows halving the cooling energy demand and, at the same time, it is effective during winter.

Concerning opaque surfaces, the effect of an external insulating coating of expanded polystyrene has been studied. The results show that a higher thermal insulation allows mitigating the wintry heat dispersions but, on the other hand, it involves a cooling energy demand increase, which can reach up to 45%.

The simultaneous use of solar control glazes and external coating turns out to be the best solution. However, the installation of new windowed elements requires very high costs and, therefore, choosing this kind of intervention needs to be accurately evaluated as a function of the initial economic budget.

In deciding which building energy retrofit measure to take, it is important to determine how quickly the energy upgrading will be repaid. Payback times can range approximately between 10 and 35 years, as a function of installation costs and required performance. The PBT evaluation performed in this work took into account only the heating system, but, as already observed, a higher insulation involves a cooling energy demand increase. It would be therefore necessary to evaluate both elements and find a proper tradeoff between winter and summer energy demands.

Author Contributions

Luca Evangelisti and Claudia Guattari designed the research and performed the measurements. Luca Evangelisti made the simulations. All the authors analyzed and discussed the data and wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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