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Renovation of a Historic Building Respecting the Preservation of Cultural Heritage Improving the Energy Efficiency

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Abstract: To achieve the European energy and climate goals by 2050, meaningful refurbishment actions are necessary for the existing stock sector, including historic buildings. A relatively new trend in contemporary design emphasizes reusing existing structures instead of constructing new ones, revisiting and reinterpreting practices that have been experimented with in the past. The pertinent question today is how to reconcile the requirements for building protection with the implementation of energy efficiency measures. In this contest stands Villa Manganelli, a creation of the renowned architect Ernesto Basile, showcasing Italian Art Nouveau in Catania from the early twentieth century. Currently, Villa Manganelli needs to be re-functionalized to enable its reuse. A master plan has been developed that encompasses both the functional changes needed to accommodate new activities and energy-efficient measures aimed at reducing the building's energy demands, all while preserving the architectural appeal of this remarkable structure. Due to the lack of data regarding the thermo-physical features of the building envelopes, the first phase of this study consists in an experimental set of measurements carried out to characterize the thermal properties of the building masonry and the indoor thermal conditions. A second phase entails the dynamic numerical simulation of the investigated building through the Design Builder software and its calibration and validation through the comparison with the experimental data. Finally, based on the developed analysis, a first hypothesis of not invasive energy efficient measures for re-functionalization of this building is presented.

Keywords: Historic; Building; Energy; Simulation; Experimental

1 Introduction

Buildings are important in EU environmental and climate plicy for their greenhouse gas emissions and high consumption of material resources. As more than 85% of today's buildings are likely to still be in use in 2050, energy retrofit could improve the sustainability of existing buildings and the implications for embedded GHG emissions and resource use [1]. Retrofitting historic buildings presents unique challenges, as the need to balance energy consumption with carbon emission reduction is essential for the long-term viability of these structures. Successful decision-making in energy retrofitting requires proper building envelope characterization for effective energy simulations [2, 3]. Estimating the physical characteristics of existing masonry can be challenging, especially for historic buildings. The main difficulties regard the identification of stratigraphy and layer composition (i.e. thickness variability, air cavities, cracks), ageing decay of the physical properties over time (composition, density, thermal performances), damage problems and moisture content [4]. Accurate assessment of the thermo-physical properties of traditional building materials is crucial to calibrate the building's energy models [5]. Different non-destructive techniques can be adopted for assessing thermal performance: visual inspections, infrared thermography, and heat flow meter measurement techniques. Infrared thermography is widely used to demonstrate the distribution of radiant thermal.

Energy emitted through building facades. This helps in the qualitative evaluation of thermal anomalies and the behavior of external walls, such as thermal bridges, different material or thicknesses, disproportionate heat loss areas, air leakages and so on [6, 7].

Heat flow meter measurement techniques (HFM) are used to measure the thermal transmission properties of homogenous building components. The Standards ISO 9869 [8] describes the apparatus, technique and data processing to be used for measuring the Thermal Resistance in opaque layers perpendicular to the heat flow. The ISO 8301 [9] defines the use of the heat flow meter method to measure the steady-state heat transfer through flat slab specimens and the calculation of its heat transfer properties. The difficulties related to the characterization of thermal properties of historical materials and masonries have usually determined an over-appraisal of the U-values compared to the actual values [10], with the overestimation of the energy consumption of historic buildings. Therefore, the application of inadequate parameters causes disadvantages for these buildings, promoting substitution or energy improvement of components [11] without any real advantage for the global energy balance. Accurate assessment of the thermo-physical properties of traditional building materials is crucial for the calibration of the building's energy models. Several studies have investigated the thermal behavior of historical buildings [12]. The energy renovation of buildings with heritage value was developed focusing on energy-efficient measures that preserve the architectural appearance of the building. Numerical simulations performed with IDA ICE software were validated with the measurements to carry out parameter variations on the energy efficient measures [13]. The thermal behavior of the building envelope strongly depends on the interaction between thermal inertia, insulation and ventilation strategies [14]. To find robust solutions for energy savings in the old heritage building stock, a thermal and economic analysis of renovation strategies for a historic building in the Mediterranean area was performed in literature [15]. About 60 packages of energy efficiency measures were analysed to evaluate if the refurbishment of historic architecture, to achieve low energy need, is possible, economically and environmentally feasible.

The research reported in the current paper analyses the thermal behaviour of "Villa Manganelli" an historical "Italian Art Nouveau" building sited in Catania, to the aim to identify intervention solutions able to improve its energy performances. Due to the lack of data regarding the thermo-physical features of the building envelopes, the first phase of this study consists in an experimental set of measurements carried out to characterize the thermal properties of the building masonry and the indoor thermal conditions. A second phase entails the dynamic numerical simulation of the investigated building through the Design Builder software and its calibration and validation through the comparison with the experimental data. Finally, based on the developed analysis, a first hypothesis of not invasive energy efficient measures for re-functionalization of this building can be proposed.

2 Material and Methods

2.1 Retrofit Criteria and Strategies

Energy retrofits in traditional and historic buildings conservation principles and energy consumption have to be considered against one another to accomplish continued, long-term use of the building. More generally, four different categories can be defined, that are global environment, building fabric, indoor environment, and economics.

Energy Retrofit impact is typically measured as yearly energy savings compared to the building as-is, and sometimes in terms of GWP emission reduction.

Embodied Energy (EE) is a metric used to quantify the benefits of building reuse, it usual represents 20–30% of the total energy used over the building's life cycle. EE can be used for comparing retrofit options based on material-related resource consumption, and for the quantitative assessment of retrofit impacts on the removal of building fabric.

The effect of the indoor environment on building occupants has to be evaluated in terms of thermal comfort, indoor air quality (IAQ), light, and sound, which jointly define the indoor environmental quality (IEQ). In this study the thermal comfort has been determined through the Predicted Mean Value (PMV).

Pollutants and inappropriate temperature and relative humidity can cause deterioration of collection hosted in historical buildings.

Table 1 lists some criteria used to assess the impact of energy retrofits in historic and traditional buildings [16].

Table 1. Classification of energy retrofit criteria in historic and traditional buildings (Adapted from [2])

Global Environment	Building Fabric	Indoor Environment	Economics
Yearly energy consumption	Conservation: (Visual and Material impact on heritage value.) Compatibility, Reversibility	Thermal comfort, Lighting, Acoustics, Indoor air quality	Capital costs, Operational energy costs
Climate change vulnerability	Hygrothermal behaviour, Thermal transmittance, Thermal mass, Thermal bridging, Moisture buffering, Air tightness	Collection: Pollutants, Inappropriate temperature and relative humidity	Maintenance and replacement costs

2.2 Dynamic Energy Analyses

The evaluation of how walls' heat storage, due to their thermal mass, affects a building's energy performance requires analyses based on transient numerical simulations.

The time lag (TL), it is defined as the time occurring for a temperature wave to be transferred from the outer wall surface $\tau\,(Tso_{\max})$ to the inner wall surface $\tau\,(Tsi_{\max})$ [17].

$$TL = \tau\,(Tso_{\max}) - \tau\,(Tsi_{\max}) \tag{1}$$

The UNI EN ISO 13786 [18] introduces the concept of periodic thermal transmittance, Ymn, to assess the thermal behavior of masonry under dynamic boundary conditions. This refers to the ability of an opaque wall to shift and attenuate thermal flux that passes through it over a 24-hour period.

The decrement factor (DF) is defined by the ratio of the amplitude of the inner surface temperature (Asi) variation to that of the outer surface temperature variation (Ase).

$$DF = \frac{Tsi_{\max} - Tsi_{\min}}{Tso_{\max} - Tso_{\min}} \tag{2}$$

3 The Villa Manganelli

Villa Manganelli, by the renowned architect Ernesto Basile, is an exemplary representation of Italian Art Nouveau located in Catania (latitude 37°47', longitude 15°05') from the early twentieth century. Notably, the main façade of the first floor and the two side towers are covered with hard limestone that is 12 cm thick. Figure 1 displays the main façade, and first floor plant.

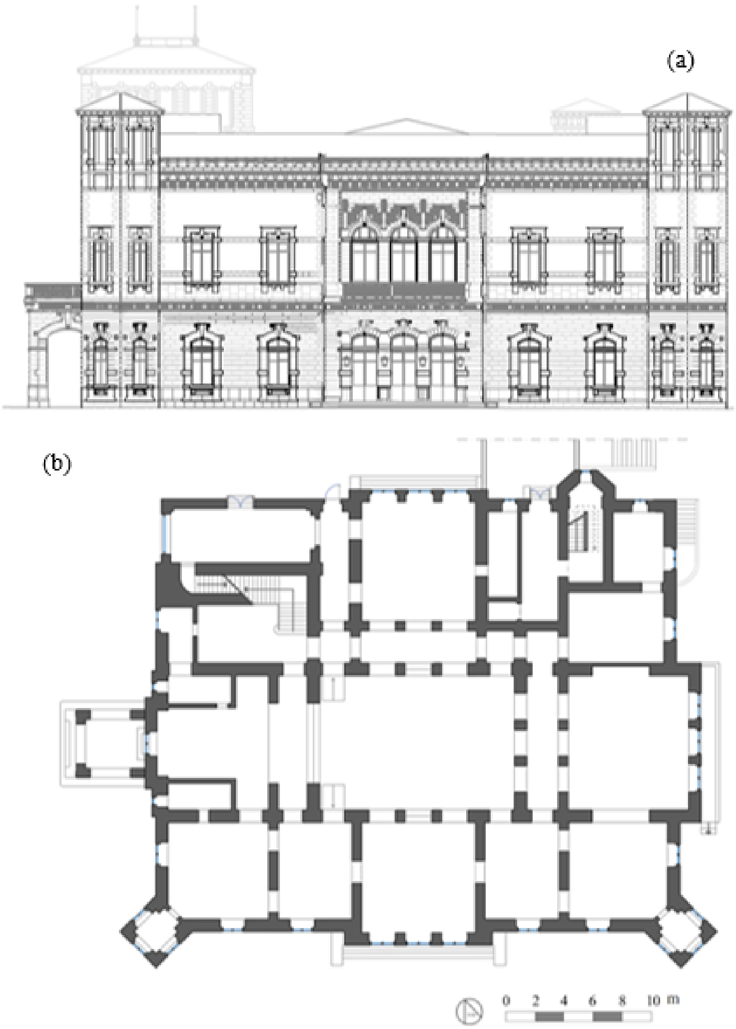

Figure 1. Main Facade and first floor plant: (a) Main Façade and (b) First floor plant

The opaque building envelope is mainly realised with masonry made of lava stone roughly squared, thermal conductivity k = 2.9 W/mK, thickness varying from 80.0 to 60.0 cm and traditional mortars. Figure 2 shows a constructive section of the masonry.

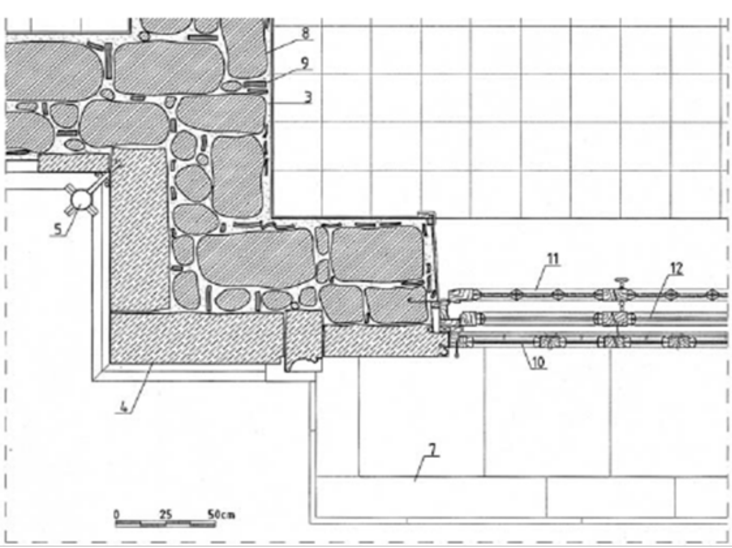

Figure 2. Constructive section of the masonry

Starting from the available data, in accordance with the UNI EN ISO 13786: 2008, the thermal transmittance (U-value) of the external wall is calculated to be 2.50 W/m^{2}K, superficial mass of 1250 kg/m^2, periodic thermal transmittance of 0.36 W/m^{2}K, Time Lag of 11.6 hour and Decrement Factor of 0.144. The French doors, recently replaced, are constituted by a wood frame and double-glazed window with U-value of 2.8 W/m^{2}K. It is evident that in the current state the building envelope of Villa Manganelli, like many other historical buildings, is extremely far away from the U-value required for new or refurbished buildings. It is essential to examine the dynamic thermal behavior of this building, particularly focusing on its thermal mass, which acts as a passive conditioning system capable of temporarily storing excess heat. During the summer months, the building's thermal mass helps to reduce peak cooling loads and maintain internal temperatures within a comfortable range by absorbing excess heat. In winter, solar and internal gains (radiant component) are stored within the walls, and then gradually transferred to the indoor environment later, contributing efficiently to reduce heating loads.

4 Experimental Survey

To characterize the thermal behaviour of this building, measurements of the indoor temperature, air velocity, relative humidity, mean radiant temperature, as well as the indoor and outdoor superficial wall temperatures have been executed.

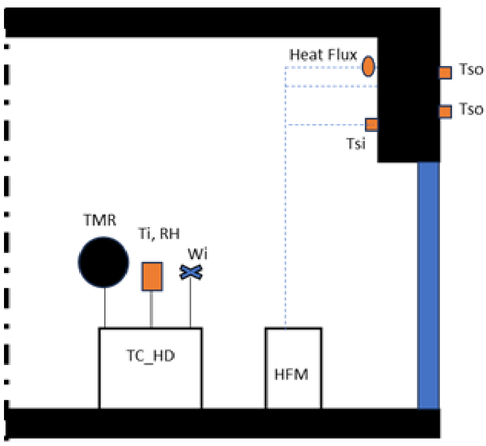

Figure 3. Layout of the equipment used

The experimental survey has been done using the wireless Heat Flow Meter ThermoZig [19] to monitor the superficial temperature and heat fluxes through the building walls. The thermal microclimate station Delta Ohm Hd 32.3 [20] was used to monitor air temperature (Ti), relative humidity (RH), velocity (Wi) and mean radiant temperature (TMR). The measurement equipment was placed in one representative room, located on the first floor, with a French door on the façade facing South. To guarantee the measurement trustworthiness, the HFM sensors were installed in a homogeneous surface portion representative of the wall avoiding the influence of singularities (e.g. thermal bridges, different thicknesses, windows). The Delta OHM HD 32.1 thermal microclimate station was placed at the centre of the investigated room, as shown in Figure 3.

Figure 4 shows the equipment used for the survey carried out. During the survey period, from February 1st to 10th 2019, the outdoor air temperatures range from 17.0 to 10.0°C, solar irradiation on a vertical façade south oriented at midday is about 600 W/m^2, which are very common values during February in Catania. And the building was maintained in free-running conditions in such a way to evaluate the capacity of the building thermal inertia, the capacity to smooth the forcing effects of weather during the day.

Figure 5 shows the measurements of the internal superficial temperature (Tsi) and the outer superficial temperature (Tso).

Figure 4. Equipment and sensors used for the survey

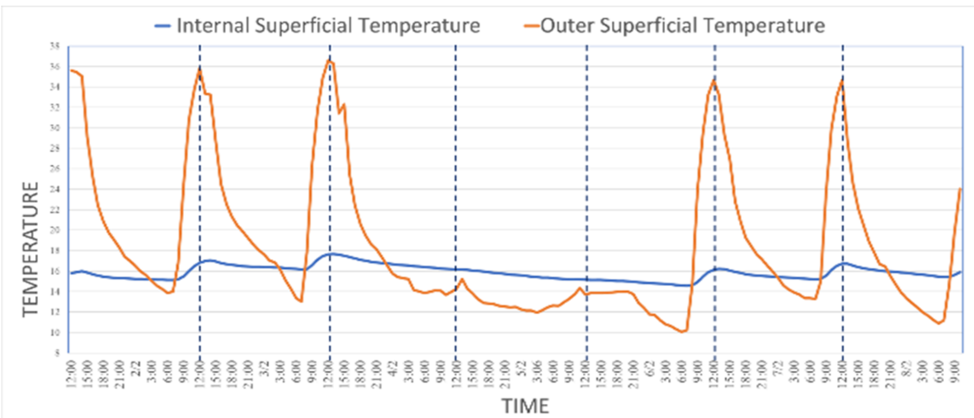

Figure 5. The measurements of the internal superficial temperature (Tsi) and the outer superficial temperature (Tso)

It is worth noting that the outer wall surface temperature varies from 36.0 to 10.0°C, while on the internal side the superficial temperature has very smooth fluctuation, from about 19.0 to 15.0°C, in accordance with the great heat capacity of the masonry. The internal surface temperature of the masonry increases from 7:00 to 12:00 and then diminishes up to 7:00 of the successive day, following the same dynamics of the temperature of the outer surface. There is almost no time delay between the peak temperatures on the outer surface ($Tso_{\max}$), and the peak of temperature on the inner surface ($Tsi_{\max}$), both at noon, is observed.

This behaviour, which at first sight could appear in contrast with the thermal inertia of the façade, is determined by the solar radiation, which goes into the room through the glass of the French door and heats the internal surface of the facade via convection and thermal radiation. However, the passive thermal behaviour of the building emerges by its capacity to maintain its mean radiant temperature always higher than 15 °C during nighttime and about 19°C at midday during the sunny days.

4.1 Building Simulation

The evaluation of the effect of the masonry thermal mass on the building's energy performance entails analysis based on transient thermal simulations. Building thermal simulation requires both the data of hourly weather conditions as well as activity and occupancy, shading systems, energy plants operations, setpoint and set-back temperatures, air infiltration rate and so on. The calculation method used by Design Builder software [21], which is used in this study, is based on two heat-balance modules. The surface-heat-balance module simulates the heat fluxes on the inner and the outer surfaces considering effects of conduction, convection, radiation and mass transfer (water vapour). And the air-mass-balance module deals with air mass streams: ventilation air, exhaust air and infiltration; it also evaluates direct convective heat gains. As concerns the evaluation of the air flow rate introduced through natural ventilation, this is a challenging task due to the complexity of the physical phenomena involved.

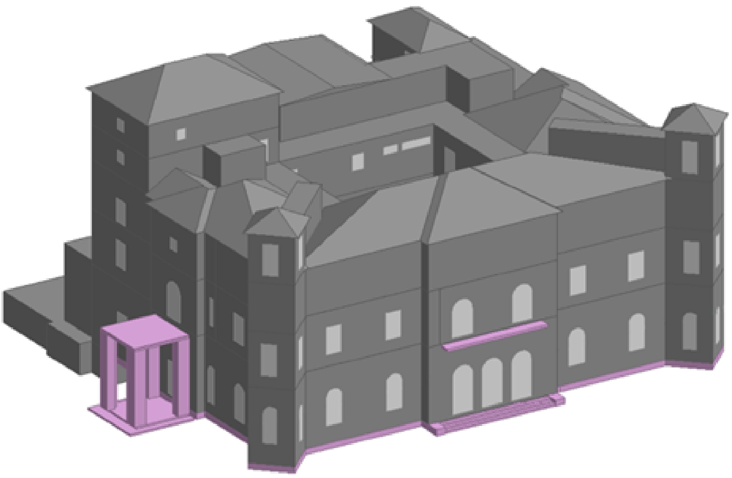

Figure 6. 3D view of the building in Design Builder

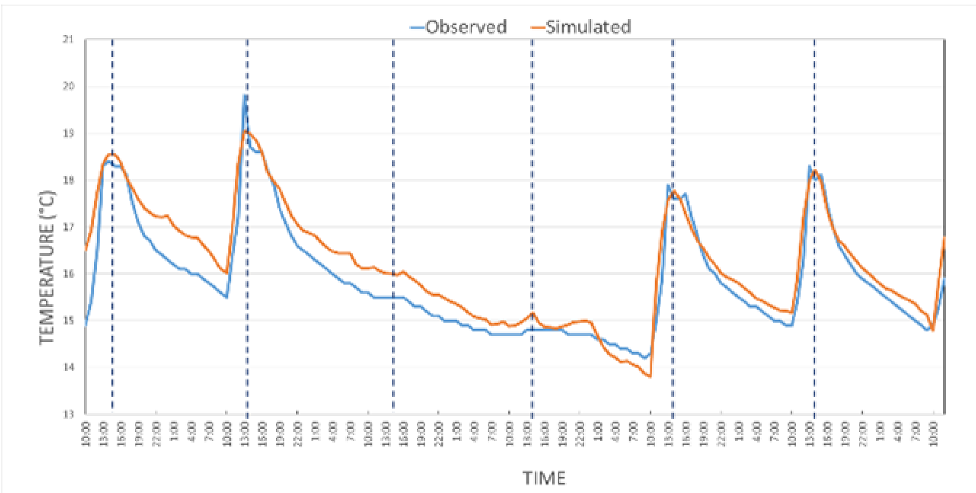

Figure 7. The comparisons between the observed and simulated indoor air temperature

The air-conditioned building must be divided into thermal zones, each one with uniform activity and occupancy schedules, shading systems, energy plants, setpoint and set-back temperatures for winter and summer as well as air infiltration rate. A virtual model of villa Manganelli has been realised, and the simulations of the building in the current state have been performed using the Design Builder software. Then, the comparison between the experimental observations, previously introduced and the results carried out through the simulations has been executed with the aim to validate the virtual model.

Figure 6 shows a 3D view of the entire building as modeled in Design Builder.

Figure 7 shows the comparisons between the observed and simulated indoor air temperature.

An excellent agreement between simulated and observed data with an R-squared value (R^2) higher than 0.92 was found. Similar comparisons have been performed also for the superficial wall temperatures confirming the reliability of the numerical model developed.

Based on these excellent results, it is possible to state that a validated numerical model of "Villa Manganelli" has been developed, which can be used for evaluating the effectiveness of the future refurbishment intervention to allow the reuse of this building as "boutique hotel". Another interesting aspect will be the activation of natural ventilation strategy for discharging the heat accumulated during the day [22, 23], indeed in localities where the diurnal variation of the air temperature is above 10 K, the decrease of the cooling load associated with the inertial effects ranges from a few percentages to more than 80%.

5 Retrofit Proposal

Starting from a proposal of reuse of Villa Manganelli as "boutique hotel", a refurbishment strategy that retains the historic and architectural attractiveness of this building has been investigated. Figure 8 shows a rendering of the hall.

Figure 8. Rendering of the hall once renovation

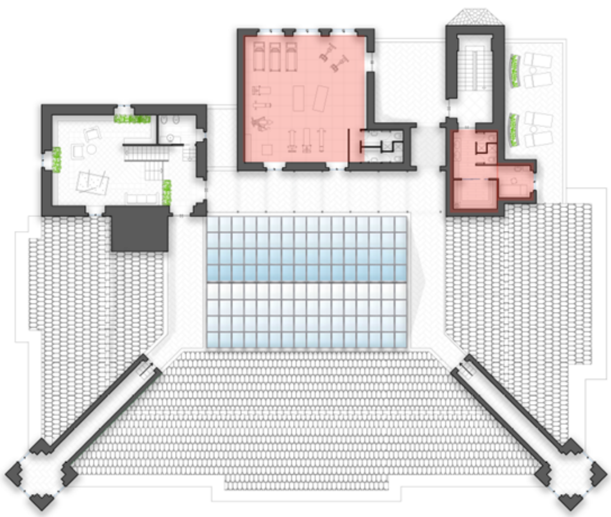

Figure 9. Roof plan, with the PV glass cover

Two main retrofit interventions are proposed, aiming respectively to improve the thermal insulation of the building envelope (opaque and transparent component):

I) Addition of thermo-plaster on the inner side of the masonry (s = 3.0 cm; k = 0.056 W/mK)

II) Substitution of the current double glass with low E glass (Uw = 1.75)

Moreover, a Photovoltaic Skylight, constituted by transparent photovoltaic glasses has been designed to shelter the internal courtyard, with an installed peak power of 4.8 kW [24], aiming to locally produce renewable energy.

Figure 9 shows the roof plan, where the PV glass cover of the courtyard is depicted.

5.1 Analyses of the Effectiveness of the Energy Retrofit Measure

In this section the effectiveness of the two measures of energy refurbishment previously introduced is evaluated. In particular, the thermal behaviour in free running conditions of the reference rooms used as reference environment has been investigated during two weeks in winter and summer.

Figure 10 shows the variation of the indoor temperature during the winter week.

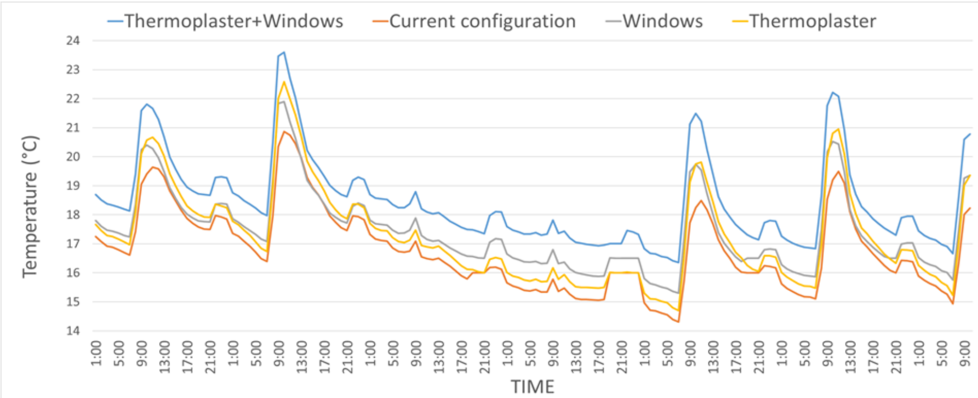

Figure 10. Indoor temperature during a winter week

It is worth noticing that the retrofit intervention, which foresees the installation of both thermos-plaster and low-e window (TP +low-e), allows achieving the highest max and min daily temperatures during the whole period. On the contrary, the current configuration has the lowest max and minimum daily temperatures. In the configuration TP+low-e, the indoor temperatures are maintained 3.5–4°C higher than those observed under the current configuration. Moreover, the minimum temperatures do not decrease below 17°C even when two cloudy days occurred, under the TP+low-e configuration. These results indicate a significant improvement in the thermal behaviour of this building.

To investigate the thermal behaviour of this building during the summer period numerical simulations has been carried out during a summer week, under the TP+low-e configuration. Figure 11 shows the variation of the indoor temperature as well as the PMV during a summer week.

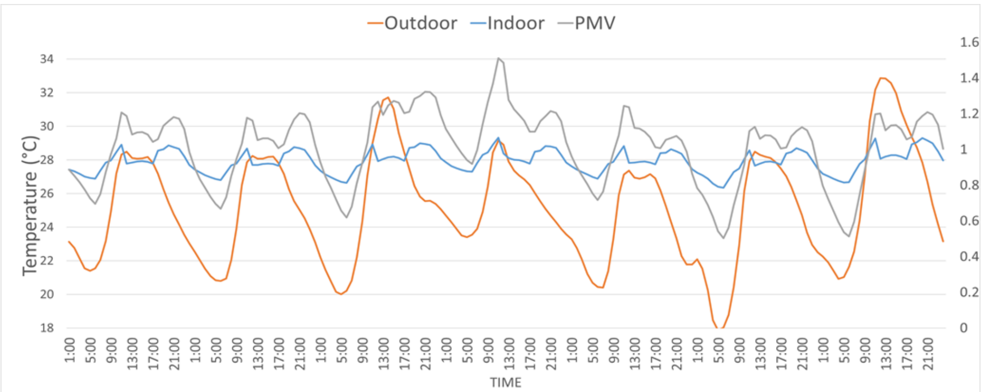

Figure 11. Indoor temperature and PMV in a summer week

It is worth noticing that the indoor temperatures remain quite constant during the week, with very smooth variations from 28 to 27°C, with value of PMV frequently higher than 1.0 (slightly warm). This indicates that during the warm season it is mandatory the use of an Air Conditioning plant.

6 Conclusions

This study has developed a numerical thermal model of "Villa Manganelli", a historical "liberty-style"building situated in Catania. The comparison between experimental data and simulation results has allowed us to verify the accuracy of the numerical model developed with the Design-Builder software. The experimental survey has highlighted the capacity of this building to strongly smooth the effects of external environmental forcing, so emphasizing its passive thermal behavior. The proposed retrofit intervention allow to notably ameliorate the thermal behavior of this building in particular during the winter period, when the operation under free-running conditions can be extensively performed, thus guaranteeing significant energy saving.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

EE	Embodied Energy
DF	Decrement Factor
GWP	Global Warming Potential
k	Thermal conductivity, $W.m^{-1}.K^{-1}$
PMV	Predicted Mean Vote
RH	Relative Humidity, %
T	Temperature, ℃
TL	Time lag, h
TMR	Mean Radiant Temperature ℃
U	Thermal transmittance $W.m^{-2}.K^{-1}$
W	Velocity, m/s