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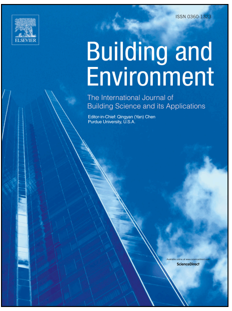

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Stressing the passive behavior of a Passivhaus: an evidence-based scenario analysis for a Mediterranean case study

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Abstract

This paper first reports the outcomes of a one-year measurement campaign of a passive house built in the Mediterranean climate of Cesena (Italy) in terms of thermal comfort parameters temperature and relative humidity and Indoor Environmental Quality (IEQ) parameter CO_2 concentrations. The design carried out with the help of the steady state Passive House Planning Package (PHPP) was able to guarantee good comfort conditions during the heating period, but on the other hand, overheating occurrences during the cooling season have been recorded for almost 50% time according to EN 15251 Standard. Further analyses conducted with the help of dynamic simulations in EnergyPlus allowed identifying the insulation levels and ventilation mode as the key design factors to change in order to reduce overheating to less than 20% of time while keeping a comfortable indoor environment in winter.

The simplifications that can be made by reducing the insulation material thickness (up to a third of the original value) on the roof and on the walls, replacing triple-glazed windows with double-glazed windows and implementing a hybrid ventilation strategy instead of using Mechanical Ventilation with Heat Recovery (MVHR) alone could also lead to economic savings. These savings, due to both lower construction costs and operational energy savings, amount to 8755 euros in terms of Net Present Value (NPV) over 30 years' time.

The Passivhaus Standard can still be regarded as a good reference for designing low-energy and comfortable houses in a Mediterranean climate if some simplifications are made according to detailed building performance simulations.

Keywords: passive house, thermal comfort, indoor environmental quality, monitoring campaign, dynamic simulation, scenario analysis

1. Introduction

In the last twenty years, the building sector in Europe changed its framework with new legislative requirements, a different real estate consistency after the economic crisis and more energy retrofitting of existing buildings. Several researchers casted light on the relations between real estate market and building energy performance [1-4], as well as on building typologies and/or technologies and their thermal performances [5-9].

As a driver to improve the building energy efficiency of both new and existing buildings, the EU approved the Directive 2002/91/CE (Energy Performance of Buildings Directive, ref. [10]) and its successive recast (Directive 2010/31/UE, also known as EPBD II [11]) that introduced the Nearly Zero Energy Building (NZEB) standard for all new constructions from 2020. This posed great challenges, especially for Southern Europe countries that are less prepared than Northern Europe ones in putting into effect the actions required to implement the NZEB standard at large scale [12].

Presently, European Commission and European Parliament are working together on a further recast of the EPBD Directive, known as EPBD III, included in the proposal of the "Clean Energy of the Energy Union" [13]. The new EPBD Directive will introduce new targets to go "*towards a low and zero emission building stock in the EU by 2050 underpinned by national roadmaps to decarbonize buildings; encourages the use of information and communication technology (ICT) and smart technologies to ensure buildings operate efficiently for example by introducing automation and control systems […]*".

This step should be accompanied by a shift from an "Energy-Performance-Approach" to a "User-Comfort-Approach" for new buildings design. In other words, beside energy performance metrics, building certification schemes should adopt Indoor Environmental Quality (IEQ) metrics and the related rating systems such as those provided in the categorization framework of EN 15251 Standard [14].

Within this framework, building comfort classification could be made both *ex ante*, i.e. during building design with the help of software simulations following a dynamic approach instead of the commonly used steady-state method suggested in ISO 13790 Standard [15], and *ex post* (i.e. after building construction) by means of on-site indoor microclimate monitoring.

In fact, as recently highlighted in a review paper of Djamila [16], the appraisal of thermal comfort predictions can be significantly affected by both uncertainties due to the choice of the correct input data for building simulation (mainly in terms of human's behavior patterns) and by the use of simple calculation models.

In this paper we further the knowledge about high-performing buildings first reporting on a one-year measurement campaign of thermal comfort and IEQ parameters of a Passivhaus built in the

Mediterranean climate of Cesena (Italy) and designed according to the Passive House Planning Package (PHPP), a simplified version of the steady-state ISO 13790 method [17-20].

Then, dynamic simulations are attempted to verify the design predictions of the PHPP and to run a scenario analysis of different technological solutions that can help solve the issues registered during the operation of the house. Linked to this, the weaknesses of the PHPP tool in capturing the transient phenomena mostly occurring in summer and transition periods are highlighted and commented, suggesting the use of more robust and detailed simulation tools for design purposes. The overarching aim is to assess if the well-established Passivhaus Standard, which typically aims at an energy reduction design approach prescribing minimum air-leakages, extra-insulation, Mechanical Ventilation with Heat Recovery (MVHR) and very efficient electric appliances, can be taken as a reference for a new user-comfort design approach according to the scheme provided by the EN 15251 Standard. An economic analysis that takes into account construction costs and operational energy needs reveals the money savings achievable.

2. Previous monitoring studies on IEQ of passive houses

From the introduction of the Passivhaus Standard in the early 1990s, several authors have reported on the energy performances achieved by passive houses during their operation. Experimental measurements have been carried out in order to see if the design goals of limiting the annual heating energy demand below 15 kWhm^{-2} and the primary energy consumption for heating, electricity and hot water production below 120 kWhm^{-2} are met. Cooling energy demand has been usually neglected, despite the delivery on 2007 of the outcomes of the passive-on project [21] that proposed the introduction – in dwellings where cooling is given mainly by means of mechanical systems – of a cooling demand threshold of 15 kWhm^{-2}. The energy consumed for cooling purposes should be accounted for in the 120 kWhm^{-2} primary energy threshold as well. Broadly speaking, the aim of the passive-on project was to test, and modify where needed, the applicability of typical design solutions born in the cold continental climate of Germany to “warmer” conditions of countries such as UK, France, Italy, Spain and Portugal. However, the main design suggestions remain the same as in the original standard, except for the possibility to reduce the amount of insulation of the envelope, raise the air infiltrations up to 1 ACH and adopt additional typical passive design solutions like shading devices on south oriented windows and natural ventilation strategies during nighttime.

The focus on the energy performances of the houses and on their indoor temperature distribution informed the biggest systematic measurement campaign conducted so far under the framework of the Cost Efficient Passive Houses as EUropean Standards (CEPHEUS) project [22]. More than 100 dwellings in Germany, Austria and Switzerland have been monitored and evaluated for compliance with the design goals set using the Passive House Planning Package (PHPP), showing overall a good agreement with the expected performances but also significant deviations due to incorrect realizations and occupants’ behavior.

More in-depth studies on the relationships between energy performance and IEQ have been recently investigated in a literature review paper [23] that shows how, despite passive houses are usually able to meet the design goals set using the PHPP, sometimes issues arise in terms of:

- Dry air conditions in winter when RH falls below 30%;
- CO_2 concentrations higher than 1000 ppm when cooking or more people are inside;
- MVHR faults in delivering the right amount of fresh air;
- Difficulties in meeting the 120 $kWhm^{-2}$ primary energy consumption threshold if the house is not equipped with very efficient electrical appliances;
- Overheating and windows operation.

Focusing on the last point, there is a consistent literature reporting on the overheating issues in certified passive houses, irrespective of the climate conditions. As an example, Rohdin et al. [24] reported on summer overheating in nine passive houses in Sweden, mainly because the MVHR system was not able to get rid of internal gains. This led to classify the houses under Category II (normal level of expectations) according to EN 15251 Standard [14].

The monitoring of 18 apartments in a social housing project in the Austrian province of Tyrol [25] not only provides evidence of summer overheating (with 20.6% of yearly hours showing indoor temperatures higher than 25°C, against a threshold set to a maximum of 10% from the Passivhaus Institut), but also of winter overheating (around 5.6% of yearly hours). The authors attribute this to the lack of external shading devices – though residents reported on the use of internal blinds during hottest days – and to a non-optimal operation of the MVHR system. This last aspect led the occupants to perform natural ventilation in addition to mechanical ventilation also during winter because of odor removal, lack of fresh air and their consolidated habits.

Ridley et al. [26] monitored the performances of two passive houses in Wales over two years, showing that the overheating risk for such very-insulated and airtight dwellings is higher than the one observed for the existing UK residential stock. In fact, despite the provision of slatted louvers manageable by the occupants, one of the dwelling failed to pass all the overheating tests set by CIBSE, PHPP and EN 15251 standards and guidelines.

The same author also carried out a detailed study of the first certified passive house built in London [27]. Again, overheating issues are found in the kitchen and living room (the hours with indoor temperatures higher than 25°C are 22.5% and 33.5% of the time respectively), despite the presence of both retractable external venetian blinds fit with an automatic solar control and of specifically designed inward-tilting windows for natural ventilation purposes.

Similar issues have been reported also for the colder climates of Scotland [28] and Estonia [29], as well as for the continental one of Slovenia [30] and Romania [31].

3. Aims and objectives

According to the previous sections, it appears evident that the delivery of comfortable and "high performing" houses by means of an energy savings design paradigm is neither obvious nor easy to obtain, even for a well-established design standard such as the Passivhaus.

This paper tackles the issue of deepening the knowledge about the performances of a passive house located in a warm environment, and starts presenting the results of one year monitoring campaign of thermal and IEQ parameters of a multi-storey apartment house located in the Mediterranean climate of Cesena (Italy) certified as a passive house. Then, with the help of dynamic thermal simulations, the following research questions are addressed:

1. Under Mediterranean climate conditions, does the Passivhaus standard provide adequate design solutions for delivering a high-quality environment throughout the year?
2. What are the key design solutions and operational strategies that could be changed/adapted, and to what extent?
3. Can these changes lead to money savings in terms of construction and running costs for heating and cooling energy consumption?

This evidence-based approach is intended to help architects and engineers involved in the design of passive houses achieving the design goal of delivering a comfortable environment for the occupants.

4. Methodology

The outcomes of a monitoring campaign of thermal and IEQ parameters of the Fiorita passive house built in Cesena (Italy) are first reported and thoroughly commented. Then, a calibrated model in EnergyPlus is employed to run hourly simulations and perform a scenario analysis aimed at identifying the passive solutions that can help solve the issues recorded during the house operation.

Finally, technical and economic considerations are discussed to deepen the understanding of the passive behavior of a Passivhaus placed in a Mediterranean climate.

4.1 Monitoring campaign

The indoor monitoring campaign concerned the measurement of air temperature (°C), relative humidity (%), CO_2 concentrations (ppm) and surface temperatures (°C) from 22/04/2016 to 22/04/2017 at an hourly time step.

The monitoring system adopted makes use of a series of probes and nodes located in the master bedroom of a duplex top floor apartment of the Fiorita multi-family passive house. The monitoring equipment, provided by Genesis Wireless Sensor Network Beeper (Beeper-WSN), is made up of:

- *Probes* to measure the physical variables air temperature, relative humidity and CO_2 concentrations. Contact temperatures are recorded via thermocouples attached to the wall and roof surfaces (see Table 1 for instruments characteristics);
- *Beesper nodes* provided with GPS sensors to collect data from the probes and to communicate the data to the Beesper Bridge via wireless connection;
- *Beesper Bridge* to collect the data from Beesper nodes and forward it to a purpose created website via GPRS signal;
- *Web Beesper Console* to allow for remote access, check and download the monitoring data.

The location of the probes is described in the next section together with the construction details of the passive house.

Table 1.

4.2 Case Study Building

The Fiorita passive house is a multi-story apartment building certified by the Passivhaus Institut (passive house ID 4086, new build) located in Cesena, in the Center-North part of Italy (see Figure 1).

The house has eight apartments of different size (four studio apartments, three apartments with three rooms and one two-room apartment). The monitored flat is the two-room apartment located at the top floor; it shows a net floor area of 49.95 m^2 and internal stairs that connect the kitchen and the living room downstairs with the master bedroom and the bathroom upstairs.

The monitoring campaign probes are located upstairs in the bedroom (see Figure 2), which is 3.5 x 4.3 m^2 large and 2.70 m high (net floor to ceiling height) for a resulting net floor area of 15 m^2, and is provided with only one external glazed door towards the balcony (1.60 x 2.32 m^2 in size). In the same Figure 2, the red circles identify the contact temperature sensors, the yellow circle shows the position of the probes used to measure indoor temperature, relative humidity and CO_2 concentrations, while the green cross refers to the beesper bridge location.

The bearing structure is made of Cross Laminated Timber (CLT), with the outer walls composed of (from the inner to the outer layer): 1.25 cm thick plasterboard, 1 cm air gap, 4 cm of rock wool insulation layer, 10 cm thick xlam panel, 10 cm of wood fiber and 10 cm of glass fiber insulating materials, 2 cm of air gap and an external wood cladding 2 cm thick (see Figure 3 left). The resulting thermal transmittance is U = 0.12 $Wm^{-2}K^{-1}$.

The walkable roof is made of 1 cm thick PVC layer, a water proof membrane of 0.5 cm thickness, 4 cm of cement screed, 32 cm of styrodur insulation material and 18 cm thick xlam panel (see Figure 3 right), with a resulting U value of 0.10 $Wm^{-2}K^{-1}$. As for the windows, they are triple-glazed PVC framed with low-emissive coating on the inner panes resulting in a center-of-glass U value of 0.60 $Wm^{-2}K^{-1}$ and a solar factor of 0.55.

Moreover, the building has been tested with the Blower Door Test according to EN ISO 9972 Standard [32] and the resulting number of Air Changes per Hour (ACH) at to 50 Pa pressure difference is n_{50}= 0.41 h^{-1}.

Figure 1.

Figure 2.

Heating and cooling are provided by means of a centralized Variable Refrigerant Flow (VRF) system served by an air-to-air heat pump that supplies also the domestic hot water, whereas dedicated Mechanical Ventilation Heat Recovery systems (MVHR) serve each apartment for ventilation purposes. Every MVHR unit shows a maximum flow rate of 230 m^3h^{-1}, a flow rate at 50% power equal to 161 m^3h^{-1}, a thermal efficiency of 90% and a Specific Power Input (SPI) of 0.31 $Wm^{-3}h^{-1}$ calculated according to EU Regulation n.1254/2014 [33].

Finally, a photovoltaic system of 14 kW peak power is installed on the roof with the aim of covering the energy needed for running the central heat pump. When PV panels alone are not able to meet the required electric power, then the national electric grid covers the remaining demand. This configuration permits to meet the primary energy requirements set by the Passivhaus as calculated with PHPP software.

Figure 3.

4.3 Thermal model and calibration process

A detailed thermal model of the monitored apartment flat has been built in EnergyPlus v.8.4 [34]. In order to keep the model as simple as possible, adiabatic surfaces have been used for both party walls and floors adjoining with other flats, assuming these flats experience the same indoor conditions. Shading surfaces with a diffuse solar reflectance of 0.3 have been used to represent the horizontal PV panels installed on the roof, the balconies, and their vertical movable grids (see Figure 4). Moreover, interior shading in the form of curtains with a solar transmittance of 0.5 is also considered for the glazed openings during cooling period (defined as from April 16 to October 14 according to [35-36]).

Two people involved in sedentary activities (heat loss of 100 W per person) are supposed to occupy the living room from 18:00 to 23:00 and the bedroom from 23:00 to 7:00 throughout the year; during these periods, internal gains consist also of various electrical equipment with a resulting power density of 3.1 Wm^{-2}. Finally, the entire apartment is served by a VRF system providing heating and cooling at every hour of the day (if needed) to keep indoor temperatures in the range of 19 to 28°C.

The calibration process aimed at comparing the measured bedroom temperatures from April 2016 to December 2016 with the simulated ones (by the time the paper has been written 2017 data was not yet available), obtained using a custom-made weather file with relevant weather data got from the local Cesena Urbana meteorological station [37].

This task showed to be challenging, mainly because of uncertainties related with flat operation from the occupants in terms of heating and cooling set points, MVHR operation and windows opening.

The results of the calibration exercise, reported in Figure 5 in the form of hourly temperature values for the bedroom only, reveal how the simulated temperatures (orange line) well follow the measured temperatures (blue line) for the entire year.

Figure 4.

Figure 5.

The daily difference between the maximum and minimum temperatures reported in Figure 6 for the measured (black line) and simulated (red line) cases respectively allows to better estimate the fluctuations that are not easily readable from the previous analysis. Overall, a good agreement is found, being the maximum difference between measured and simulated temperatures as depicted by the yellow area in the graph of slightly less than 1.5 °C, while the average annual difference amounts to just 0.39 °C.

Figure 6

The frequency distribution of the daily average error has been calculated as well and reported in Figure 7. Here it is possible to see how the average daily error is always within the range of -1.5 to 2 °C, being within the range of -1 to 1 °C for 71% of the time and showing a mean error value of -0.09 °C on an annual basis. This is considered a very positive result given the above-mentioned uncertainties of the model.

Figure 7.

Finally, to better substantiate the agreement between measured and simulated indoor temperatures, some statistical indicators such as the coefficient of determination R^2, the Mean Bias Error *MBE*, the coefficient of variation *CV* and the *Pearson coefficient* have been calculated according to Equations (1-4):

$$R^2 = \frac{\sum_{i=1}^{n}(S_i - \bar{M})^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \tag{1}$$

$$MBE = \frac{\sum_{i=1}^{n}(M_i - S_i)}{\sum_{i=1}^{n} M_i} \tag{2}$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{n}\left[\frac{(M_i - S_i)^2}{N_i}\right]}}{\frac{\sum_{i=1}^{n} M_i}{n}} \tag{3}$$

$$PEARSON = \frac{\sigma_{MS}}{\sigma_M \sigma_S} \tag{4}$$

here M_i and S_i are the measured and simulated temperatures respectively, $\overline{M}$ is the average measured temperature, n is the number of measurements, σ_{MS} is the covariance between measured and simulated temperatures and σ_M (σ_S) is the standard deviation of measured (simulated) temperatures respectively.

The resulting values are reported in Table 2, and according to the hourly calibration method suggested by the ASHRAE Guideline 14-2014 [38] (though this document mainly pertains to the calibration of the simulated energy demand) a strong correlation is found so that the model can be considered well calibrated.

Table 2.

4.4 Scenario analysis and IEQ metrics

Based on the outcomes of the monitoring campaign, different scenarios are simulated in EnergyPlus to further stress the passive behavior of the house and appraise the benefits that can arise from simplifying the existing layout, mainly in terms of insulation levels and ventilation strategy. In detail, the following scenarios are considered:

a) Free running (with and without a natural ventilation strategy);
b) Double-glazed windows with low-emissive coating are used in place of the existing triple-glazed low-emissive ones (free running operation, natural ventilation implemented);
c) Same as b) but with less insulation on the outer walls and on the roof;
d) Same as c) but with the MVHR system in operation and a hybrid ventilation strategy implemented.

In terms of natural ventilation, a basic control strategy is considered: the windows can be opened, throughout the year, when indoor temperature is higher than 19°C (which is the actual set point temperature for heating) and outdoor temperature is at least 2°C lower than inside. The maximum air change rate achievable has been set to 2ACH, deemed as a reasonable value when not performing more detailed CFD analysis [39]. This control strategy has been checked with preliminary simulations and it avoids overcooling occurrences in winter and transition periods.

For what concerns scenarios b) and c), the existing construction components have been changed – by reducing the thickness of the insulation layers – in order to meet the minimum requirements set by the Italian building codes in terms of U-values for buildings located in climate zone E, where Cesena pertains, to be built after January 2019 [40]. As a result, windows have a U-value of 1.40 $Wm^{-2}K^{-1}$, while the roof and the outer walls have U-values of 0.22 $Wm^{-2}K^{-1}$ and of 0.26 $Wm^{-2}K^{-1}$ respectively.

The scenarios described above will be then compared in terms of indoor/operative air temperature distribution for the sake of classifying the house according to the three IEQ categories defined in EN 15251 Standard [14] (see Tables 3-4) and analyzing potential overheating issues. To this aim, different tests will be performed: the first one refers to the calculation of the hours when the operative temperature is higher than 27°C (i.e. above the upper threshold of Cat. III of comfort), the second one is conducted according to the Passivhaus overheating criterion (i.e. overheating occurs when indoor temperatures are higher than 25°C for more than 10% of the annual hours), and the last one by also considering the intensity of overheating by calculating the amount of degree hours above the previous thresholds.

Finally, relative humidity and CO_2 concentrations are analyzed for the monitoring campaign in order to see if and to what extent they represent an issue for the occupants, but given their strong dependency on human behavior and indoor sources generation they will not be further considered in the scenario analysis described above.

Table 3.

Table 4.

5. Results

5.1 Monitoring campaign: evidence of the issues recorded

Indoor temperatures registered during the monitoring campaign kept well within the range of 19°C to 28°C, even when the outdoor temperature reached the summer peak of 38°C on July 12 and the winter peak of -3°C on December 19. The average winter temperature is 20.7°C, while the average summer temperature is 25.2°C. Furthermore, the amplitude of the oscillations is very low (see Figure 8), and this can be explained first because the very high level of insulation of the opaque envelope helps retaining the heat in winter and reduce the heat incoming in summer. Secondly, solar gains are well managed thanks to the optimal orientation of the building, the low windows U-value and the good shading design (balconies and movable external panels namely). Finally, the airflow is strictly controlled thanks to the excellent airtightness of the envelope and to the MVHR system that modulates the required flow rate to meet thermostat requirements set by the occupants.

This last point is of particular interest because actually the occupants reported the opening of the windows sometimes for letting fresh air in and cooling the indoor when they deemed this as “suitable” (reasonably during late evening and night when outdoor temperature is lower), meaning that either MVHR was not well operating or they simply prefer to open the windows.

Figure 8.

The EN 15251 Standard states that indoor climate Category II should be used for new buildings assessment [14], as in this case. However, from the monitoring campaign it emerged – despite the house is designed and built according to the high quality requirements set by the Passivhaus – how seldom indoor temperatures fall within this category. In order to have a better understanding of this issue, Figure 9 reports IEQ classes achieved for the heating and cooling seasons separately according to the ranges shown in Table 3. What appeared is that during the heating season the IEQ is by far better than in the cooling season: in fact, indoor temperature is within the first two classes of quality for 45% of time during the heating period (from October 15 to April 15), against 24% of time of the cooling period (from April 16 to October 14). Furthermore, overheating (i.e. those occurrences when temperature is higher than the threshold of 27°C set for Cat. III) accounts for 48% of the time meaning that occupants may not feel comfortable in such a time frame. For the remaining 2% of time temperature is tagged as “no cooling” period because it is lower than the threshold of 22°C (see Table 3).

Figure 9.

In terms of relative humidity, the recorded values shown in Figure 10 show how for most of the time they are within the band of 30 to 70%, with just few occurrences below (41 hours) and some above (1063 hours) this range. The maximum value is 77%, the minimum is 25% and the average is 53% respectively. Overall, it can be stated that relative humidity is within the comfort boundaries for most of the time (around 81% of the monitored time) and does not represent an issue.

Figure 10.

According to Annex B of EN15251 Standard (ref. [14]), there are three methods for categorizing buildings in terms of ventilation air flow: i) method based on person and building component, ii) method based on ventilation rate per person (or per m^2 floor area) and iii) recommended values for CO_2 dilution. In this work, we chose this last method (please see Table 4 for the relevant thresholds).

In terms of CO_2 concentrations, both the occupancy pattern and the operation of the MVHR system guarantee good indoor conditions: in fact, the bedroom is classified within Cat. I for 80% of the time, while being in Categories II and III for 8% of time each and in Cat. IV for just 4% of time (see Figure 11). It can be safely stated that, as for relative humidity values, indoor CO_2 concentrations are not a problem.

Figure 11.

Finally, indoor surface temperatures have been analyzed to see if asymmetries characterize the indoor space, and are reported in Figure 12 as a red line for the ceiling and as a black line for the wall marked with the red point in Figure 2. Overall, it appears that the trends are quite similar, with ceiling temperatures being slightly higher than wall temperatures of 0.4°C on average (within the instrument accuracy range of 0.5°C) and of 1.1°C during peak conditions in summer and winter (the circle areas highlighted in Figure 12). This happens because the room monitored is just below the roof, so the solar radiation makes the incoming heat flux higher than that through walls despite the shading provided by PV panels.

Figure 12.

5.2 Scenario analysis

The first scenario considers a purely free-running operation of the building, so the only difference with the existing case is the absence of the VRF and MVHR systems. The corresponding indoor temperatures have been plotted in Figure 13 with a green line: it is straightforward to notice how temperatures now span from 15°C in January to around 38°C in June and occasionally in October, with consistent overheating conditions according to the Passivhaus standard from April until late November. This behavior can be easily explained thanks to the super-insulated and airtight envelope that keeps the heat inside very well (indeed heating would be required just for few hours in January and February) but, on the other hand, cannot effectively dissipate it when it is too warm without a proper ventilation strategy. Following the Passivhaus design requirements, this task should be accomplished by a MVHR system with a heat recovery efficiency of at least 0.75, but because this paper tries to fully exploit the potential of passive solutions the natural ventilation strategy described in Section 4.4 is considered instead.

The outcomes of this scenario have been reported in the same Figure 13 with a blue line in order to easily compare the benefits achievable. Apart from showing the same behavior of the case without natural ventilation until middle of February, from this point onwards temperatures are consistently lower (up to 7°C less in transition periods such as May and October) and within the range of 15°C to 31°C. Noticeably, overcooling hours (i.e. those hours when indoor temperature is lower than 18°C) accounts for only 6% of time, meaning that heating would be required for few hours in a year (around 500 hours in total).

Figure 13.

However, overheating is still an issue, so other passive measures have to be sought to render indoor conditions more comfortable and stable throughout the year. Building upon the free running case with natural ventilation implemented (hereafter called scenario a) described above, other two completely passive scenarios are considered: one makes use of double-glazed windows with low emissive coating (scenario b), and the other one couples these windows with a less insulated opaque envelope (scenario c). For the sake of clearness and brevity, the performances of these two scenarios will be presented in terms of IEQ classes for heating and cooling periods (see Figure 14) and of overheating analysis (see Figure 15) together with the outcomes of all the remaining scenarios. Annual indoor temperature distributions are not reported because the different trends would not be readable at this time scale.

An additional scenario that considers insulation thickness reductions on the roof and on the walls while keeping the original triple-glazed windows was run as well, but the outcomes are almost identical to those achieved by scenario c) so we prefer to discuss only the latter. Further, the use of double-glazed windows can effectively reduce construction and running costs, as discussed later.

The classification of IEQ conditions according to EN 15251 Standard reports interesting results worth of discussion. As far as the heating season is concerned (left hand side of Figure 14), the existing scenario shows the highest number of hours within Cat. I (25% of the heating hours), strictly followed by scenarios a) and b) with around 22% of time. Nonetheless, overcooling is experienced for 31% of time in the existing scenario while this figure drops down to 11% and 18% for scenarios a) and b) respectively. What changes among the existing, a) and b) scenarios is thus the amount of hours experienced in overcooling and Cat. III classes, since the amount of hours spent in Cat. II is almost the same in all cases and amounts to around 5%.

The other passive scenario, i.e. Scenario c), performs the worst in terms of overcooling (45% of time), being within the boundaries of Cat. I for 17% of time, of Cat. II for 7% of time and of Cat. III for the remaining 31% of time.

Finally, scenario d) shows the lowest number of hours within Cat. I (only 6%), being for 6% of time in Cat. II and 88% of time in Cat. III but without experiencing any overcooling at all.

Figure 14.

On the contrary, during the cooling period the best performances are achieved by scenarios c) and d), with 35% of the time classified as Cat. I, 13% as Cat. II, 21% as Cat. III and 11% as "no cooling". The authors have introduced this category to explicitly account for temperatures lower than 22°C (lower cooling threshold of Category III). However, for the remaining of the time (around 20% of cooling hours), the room will still suffer from overheating.

The existing scenario behaves the worst in terms of operative temperature distribution, with 49% of the time tagged as overheated (see Figure 14 on the right hand side), 15% of time classified under Cat. I, 8% of time under Cat. II, 26% of time to Cat. III and the remaining 2% tagged as no cooling.

Scenarios a) and b) behave pretty much the same, and in between the existing scenario (the worst) and scenarios c) and d) (the best).

5.3 Overheating analysis

Overheating issues have been assessed first calculating the number of hours in a year with indoor temperatures higher than 25°C as suggested by the Passivhaus standard, together with the number of hours when the threshold of 27°C for the operative temperature is exceeded (EN15251 Standard). This calculation is reported on the left side of Figure 15. According to the Passivhaus overheating criterion, all the scenarios analyzed report overheating issues because in every case the threshold of 10% is largely exceeded. What is interesting to note is that all the scenarios analyzed using this criterion report a number of overheating hours that is higher (even more than double) than what is predicted according to the EN 15251 methodology, except for the existing configuration.

This can be likely explained by the radiant asymmetries recorded within the room (see Figure 12), which are likely due to the operation of the MVHR system that sometimes does not provide a sufficient amount of fresh air to effectively discharge the heat stored in the roof structure in the existing configuration. In such cases, the indoor air temperature is a poor comfort indicator and should be put aside in favor of the operative temperature.

Figure 15.

To have also an idea of the magnitude of these overheating occurrences, the number of degree hours above the limit has been calculated as well and reported on the right side of Figure 15.

What is worth to note is that the general trends keep consistent with the previous analysis, with the intensity of overheating predicted by using the operative temperature threshold of 27°C being by far lower than what is predicted using the indoor temperature threshold of 25°C as an indicator, except for the existing configuration. This can be explained noting that, despite the indoor temperature is higher than 25°C, it is seldom higher than 27°C for scenarios a) to d) and thus the operative temperature (which can be defined as the average between the indoor and mean radiant temperatures) exceeds the 27°C threshold for a few number of hours. Once again, it seems the operative temperature is a better indicator than the indoor air temperature for predicting overheating.

5.4 Economic analysis

The simulation exercise carried out on the study passive house showed that it is possible to achieve better thermal and IEQ conditions than actual ones by modifying the existing building layout. Moreover, the construction process can be significantly simplified by reducing the amount of insulation installed on the walls and on the roof, using double-glazed windows in place of triple-glazed ones and avoiding the use of a MVHR system in favor of a completely passive natural ventilation strategy or low-energy systems such as fans.

For both designers and occupants, it would be of interest to report on the economic savings achievable in terms of construction costs and running costs for heating and cooling energy consumption for each scenario discussed previously, and thus answering the third research question initially placed. Actual costs for the existing case, relative to the surveyed flat only, are compared with those obtained from the local specifications for public works for the latest year available in Cesena area (2016) and from direct communication with the house designer. As for the price of electricity, it is set to 0.19 €kWh^{-1} according to the Italian Authority for Energy and Environment Regulation (ARERA, ref. [41]).

If looking at the results reported in Table 5, there appears that construction costs savings range from 4251 € when MVHR is employed (scenario d, hybrid ventilation strategy) up to 10751 € for scenario c.

If considering running costs savings, a completely passive operation of the house (scenarios a, b and c) allows to save around 130 € per year on the electricity bill, which represents the running cost of the existing scenario for heating and cooling provision. On the other hand, when the MVHR system is run in conjunction with a natural ventilation strategy (scenario d), this figure drops down to around 10 € per year.

This happens because, despite the insulation levels are worsened and heating consumption increases from 3.62 $kWhm^{-2}$ to 6.11 $kWhm^{-2}$, the cooling energy savings (from 10.01 $kWhm^{-2}$ to 6.44 $kWhm^{-2}$) exceeds the heating penalties and allows for modest running costs savings.

Table 5.

To appraise the convenience of scenario d) in a long term perspective, the difference in Net Present Value (NPV) between this and the existing case has been calculated as well over 30 years' time span. To this aim, an inflation rate of 1.1% according to the latest available report released by the Italian National Institute of Statistics (ISTAT, ref. [42]), and an interest rate of 2% as gathered from Bank of Italy historical data for year 2018 [43], have been used.

The value thus obtained is positive and amounts to 8775 €, meaning that there is an economic convenience in choosing scenario d) over the existing baseline. The NPVs of the other scenarios have not been calculated because in spite they would guarantee much higher returns it is not realistic to assume the construction of a Passivhaus without any HVAC system in use.

6. Discussion

This paper analyzed thermal and IEQ conditions in a bedroom placed under the roof of a passive house located in the Mediterranean climate of Cesena (Italy). Because of its location (top floor of a multi-storey building), the overheating issues may be slightly bigger than those of a middle-storey room and not fully representative of an average behavior of the house, although the high roof insulation level and the shading provided by PV panels counterbalance this effect. Moreover, the building appears correctly oriented, with majority of the windows exposed due to south and well shaded by the balconies and by external shadings provided in the form of vertical movable panels. In a nutshell, it is possible to state that it follows the guidelines suggested by the passive-on project [21] and can be considered an example of good practice design. The outcomes of this study can thus be regarded as representative of the issues encountered when building a passive house in the Mediterranean climate, though more case studies are encouraged to draw conclusions that are more robust.

In order to answer the first research question, *“does the Passivhaus standard provide adequate design solutions for delivering high-quality environments throughout the year?”*, what emerges from the monitoring and scenario analysis presented above is that the use of the steady-state method implemented in the PHPP does not guarantee the achievement of good comfort conditions during the cooling season. Indeed, the use of a dynamic software such as EnergyPlus helped identify the key design solutions and operational strategies that could be changed/adapted (research question 2) in the insulation levels and ventilation strategies namely. In particular, using the insulation thicknesses strictly necessary to meet the prescriptions set by the Italian building codes for roofs and walls (10 cm and 8 cm respectively for the study construction packages) already allows reaching good comfort conditions in winter and lower indoor temperatures in summer, thus significantly reducing overheating occurrences from 50% to less than 20% of cooling time (see Figure 14). The use of double-glazed windows with a low-emissive coating on the inner pane points to the same direction. What appears trickier from a designer perspective is the provision of a good ventilation strategy to successfully get rid of the heat inside while satisfying the requirements for fresh air supply. As reported in Section 5.1, and confirmed by the occupants of the surveyed flat, windows were opened from time to time because the MVHR system was not deemed appropriate to satisfy their comfort needs.

Furthermore, the economic analysis of Section 5.4 showed that reductions in the construction and running costs could be achieved by implementing these passive design measures.

For all these reasons, it is in the authors’ opinion that it is safe to choose option d) because some heating and cooling is still needed throughout the year, but the MVHR system may be replaced with single split units working as heat pumps (one for the bedroom and one for the living room). Indeed, the unitary cost of a split unit with high Coefficient of Performance (COP) in the heating mode and Energy Efficiency Ratio (EER) in the cooling mode seldom exceeds 800 €, thus significantly increasing the economic savings achievable in terms of construction costs to around 9000 € while adding the benefits of an easier operation and electricity supply from PV panels.

7. Conclusions

The shift from an energy savings design approach to a comfort user design approach should be encouraged not only in light of the latest normative requirements set by the European Union, but also as a natural development of the broader architecture discourse.

Among a variety of building design standards, the Passivhaus stands out as one of the more prominent and widely used since its born in the 1990s. Despite this, the literature reports on few studies focusing on IEQ conditions rather than on the merely energy performances of these passive houses, especially in warm climates like the Mediterranean one. This paper addressed this gap by reporting on a one-year measurement campaign of indoor conditions for the Fiorita passive house, a multi-family apartment block located in Cesena (Italy). The outcomes revealed how the design carried out using a steady state tool such as the PHPP achieved the goal of delivering good comfort conditions during the winter period, with around 45% of heating hours falling within the first two Classes of comfort categorized by the EN 15251 Standard. On the other hand, despite the provision of shading devices and the operation of a MVHR system to get rid of excessive heat inside, the house failed to ensure high comfort levels in summer. In fact, overheating was experienced for almost 50% of time during the cooling period, an issue that has been analyzed in detail by means of dynamic simulations in EnergyPlus.

The outcomes of the scenario analysis showed that overheating hours could be drastically reduced to less than 20% of time if lowering (up to a third) the insulating materials thickness applied to the roof and to the walls, as well as using double-glazed low-emissive windows in place of triple-glazed ones. Moreover, implementing hybrid or natural ventilation strategies instead of relying on the operation of the MVHR system alone adds additional benefits in terms of summer comfort and operational use. Indeed, it is not easy to achieve a flow rate balance able on the one hand to get rid of internal gains and on the other hand to satisfy the occupants' needs of fresh air, usually achieved by opening the windows.

The simplifications in the building layout that can be achieved if following these measures have a noticeable impact also on construction costs and running costs for heating and cooling provision for a surveyed apartment. In fact, the economic savings related to the reduced construction costs could range from 4251 € when using a hybrid ventilation strategy via the existing MVHR system up to 10751 € under a completely passive operation of the flat. If taking into account also the operational costs due to heating and air conditioning over a time span of 30 years for the hybrid ventilation scenario analyzed, the NPV calculation is positive and amounts to 8775 €. This happens because economic savings are expected also from the electricity savings due to the measures proposed (from 13.63 $kWhm^{-2}$ of the existing scenario to 12.55 $kWhm^{-2}$ of the hybrid ventilation scenario).

In conclusion, although more case studies are encouraged to draw more robust conclusions, the implementation of the Passivhaus Standard under Mediterranean climate conditions poses challenges that can be successfully solved if more detailed building performance predictions are performed in the design stage using dynamic tools rather than the prescribed steady-state PHPP.

Nomenclature

Abbreviations

ACH	Air Changes per hours (h^{-1})
CFD	Computational Fluid Dynamics
CLT	Cross-laminated timber
CMV	Controlled Mechanical Ventilation
CV	Coefficient of Variation
CV (RMSE)	Coefficient of Variation (Root Mean Square Error)
HVAC	Heating Ventilation and Air-Conditioning
IEQ	Indoor Environmental Quality
EIFS	Exterior Insulation and Finishing System
EPBD	Energy Building Performance Directive 2002/91/CE
EPBD II	Energy Building Performance Directive (recast) 2010/31/CE
EPBD III	Energy Building Performance Directive (proposal)
MBE	Mean Bias Error
MVHR	Mechanical Ventilation and Heat Recovery
n_{50}	air change rate at 50Pa
NPV	Net Present Value
NZEB	Nearly Zero Energy Building
PHPP	Passive House Planning Package
PV	Photovoltaic
R^2	Coefficient of determination R^2
SPI	Specific power input (heat pump)
VRF	Variable refrigerant flow (HVAC technology)

Greek letters

σ	covariance

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Table 1. Instruments characteristics

Variable	**Accuracy range**	**Measurement range**
Air temperature	±0.5 °C	0-50 °C
Relative humidity	±3 %	20-80 %
CO2 concentrations	±50 ppm	0-5000 ppm
Contact temperatures	±0.5 °C	0-50 °C

Table 2. Statistical indicators from the calibration process

R^2	MBE	CV	PEARSON
0.78	-0.46%	38.7%	0.88

Table 3. Recommended operative temperatures according to EN 15251 Standard [17]

Type of building or space	**Category**	**Temperature range for heating (°C)** **Clothing – 1.0 clo**	**Temperature range for cooling (°C)** **Clothing – 0.5 clo**
Residential buildings Sedentary activity (~1.2 met)	I	21.0-25.0	23.5-25.5
	II	20.0-25.0	23.0-26.0
	III	18.0-25.0	22.0-27.0

Table 4. Recommended CO_2 concentrations according to EN 15251 Standard [17]

Category	**Corresponding CO_2 above outdoors (ppm)**
I	350
II	500
III	800
IV	>800

Table 5. Construction and running costs savings of the different scenarios

Scenario	**Insulation costs** (roof surface of 25 m^2,wall surface of 60 m^2)	**Windows costs** (windows surface of 3.7 m^2)	**MVHR costs**	**Construction costs savings**	**Electricity consumption**			**Running costs savings** (floor area of 49.95 m^2)
					heating	**cooling**	**total**	
existing	60 € m^{-2}	676 € m^{-2}	6500 €	-	3.62 $kWhm^{-2}$	10.01 $kWhm^{-2}$	13.63 $kWh\ m^{-2}$	-
a	60 € m^{-2}	676 € m^{-2}	-	6500 €	-	-	-	129.35 €
b	60 € m^{-2}	400 € m^{-2}	-	7521 €	-	-	-	129.35 €
c	22 € m^{-2}	400 € m^{-2}	-	10751 €	-	-	-	129.35 €
d	22 € m^{-2}	400 € m^{-2}	6500 €	4251 €	6.11 $kWhm^{-2}$	6.44 $kWhm^{-2}$	12.55 $kWhm^{-2}$	10.25 €

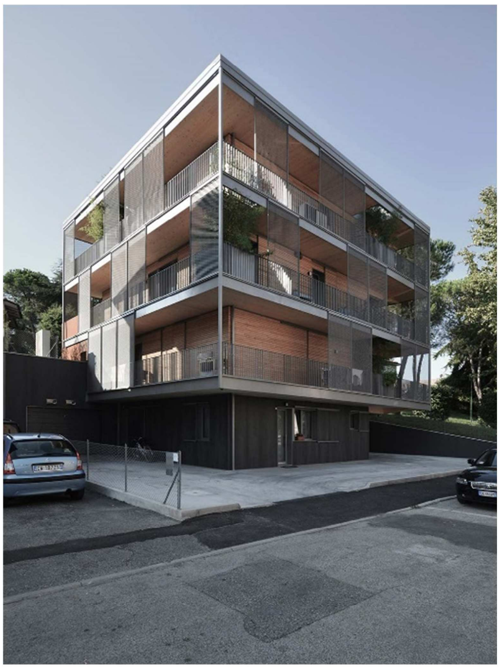

Figure 1. Outdoor view of the Fiorita passive house

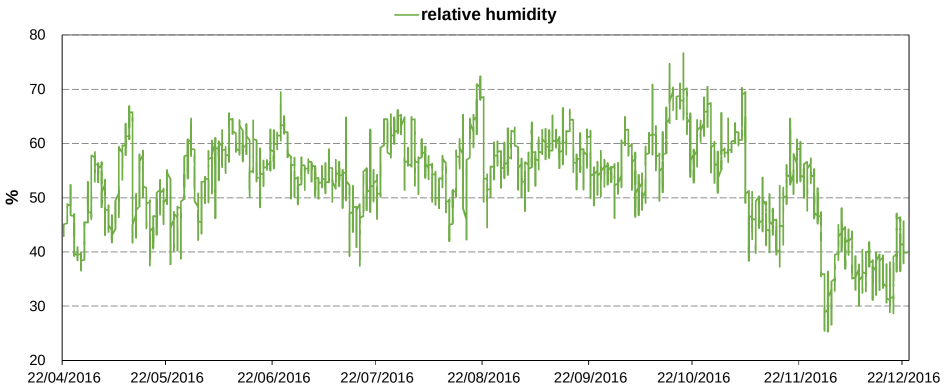

Figure 10. Indoor relative humidity values during the monitoring campaign

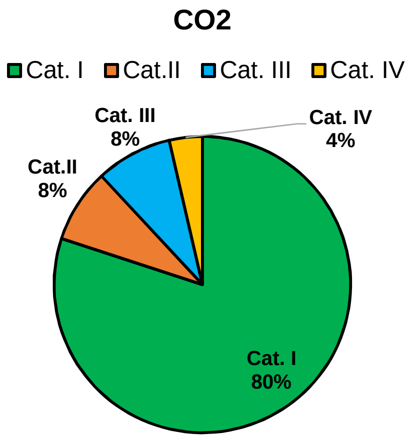

Figure 11. IEQ classes for CO_2 concentrations

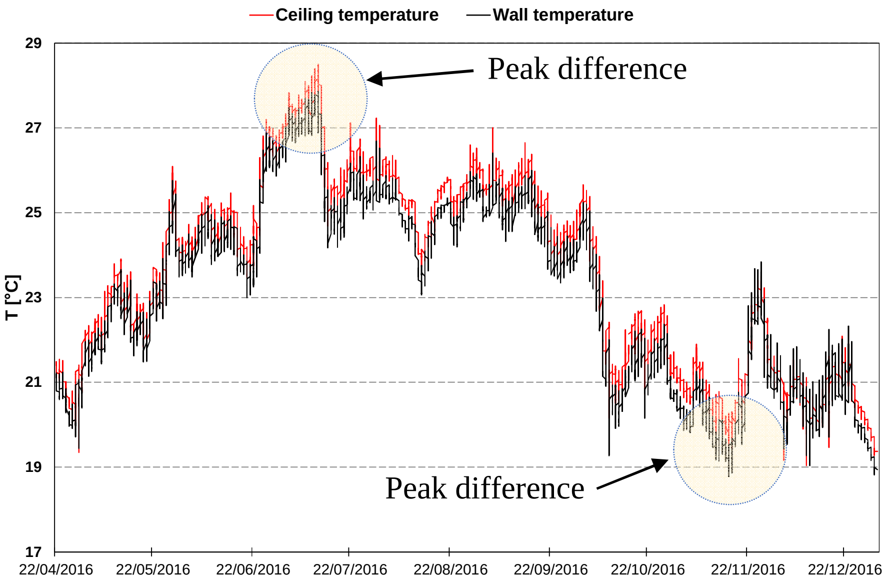

Figure 12. Ceiling and wall temperature trends during the measurement campaign (the highlighted zones identify major deviations)

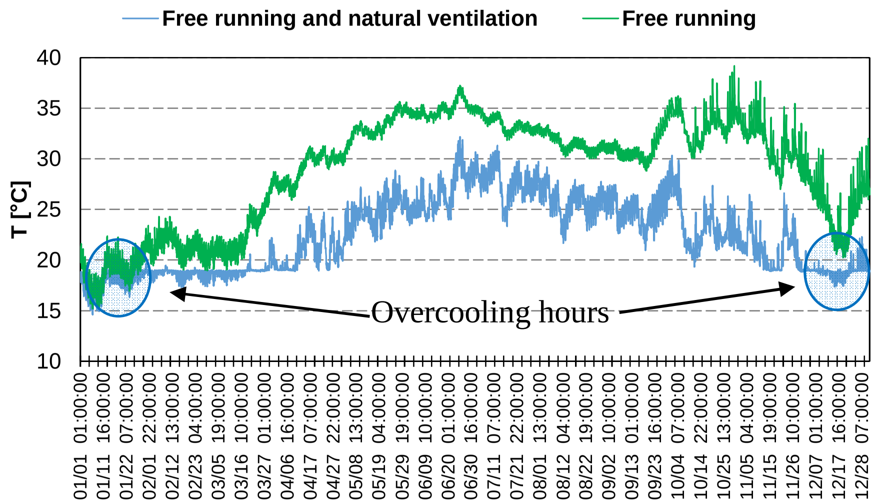

Figure 13. Indoor temperature trends under free running operation (green line) and with a natural ventilation strategy implemented (blue line)

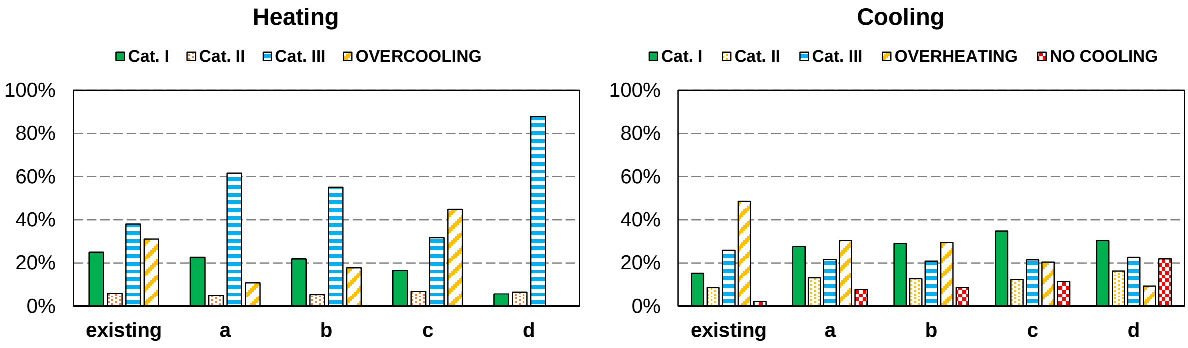

Figure 14. IEQ classes for the different scenarios under the heating season (on the left) and cooling season (on the right)

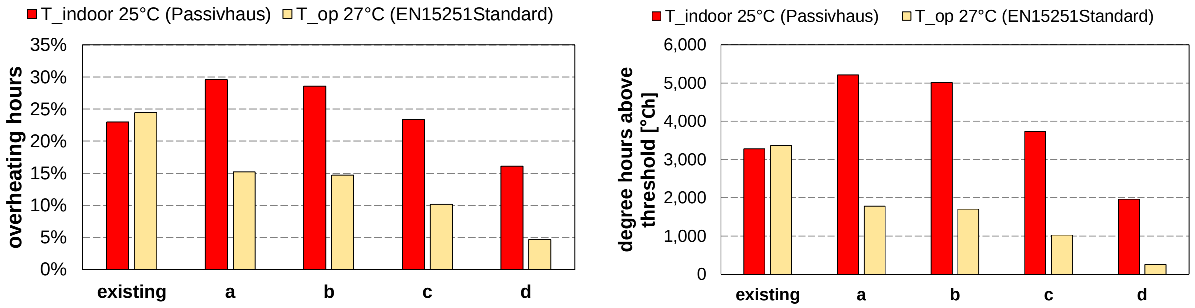

Figure 15. Overheating hours (on the left) and degree hours above the limit (on the right) for the different scenarios according to the Passivahus (red bars) and EN15251 Standard (yellow bars)

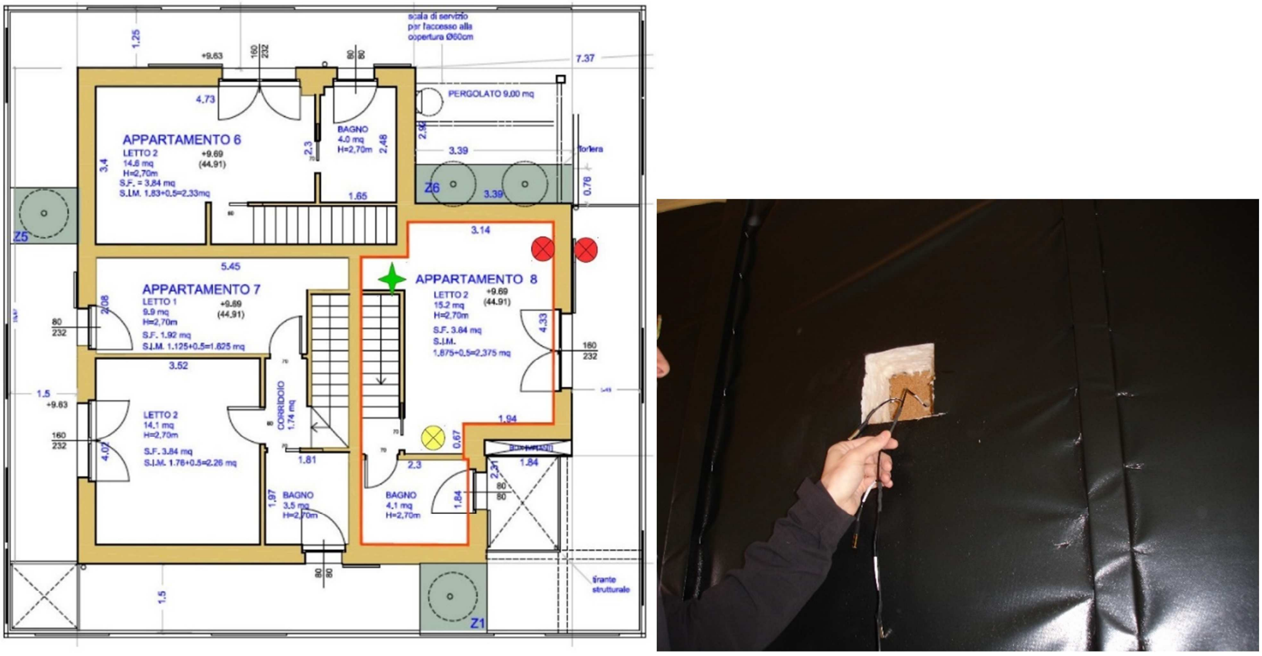

Figure 2. Floor plan of the monitored flat (on the left) with the location of the monitoring instruments and placement of a contact temperature sensor on the external wall (on the right)

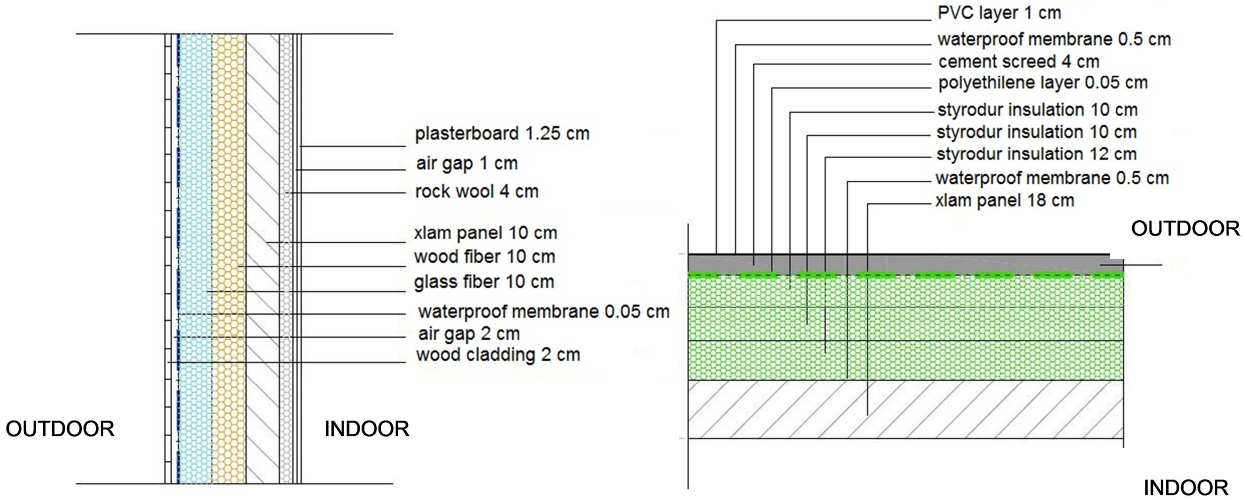

Figure 3. Construction layers of the external walls (on the left) and of the roof (on the right)

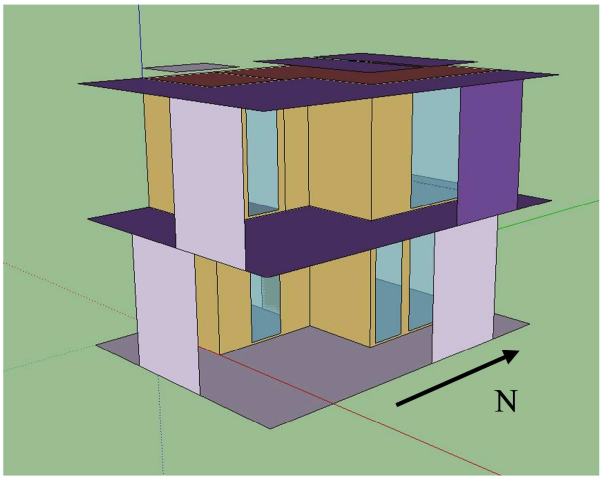

Figure 4. Axonometric view of the thermal model (shading surfaces in purple)

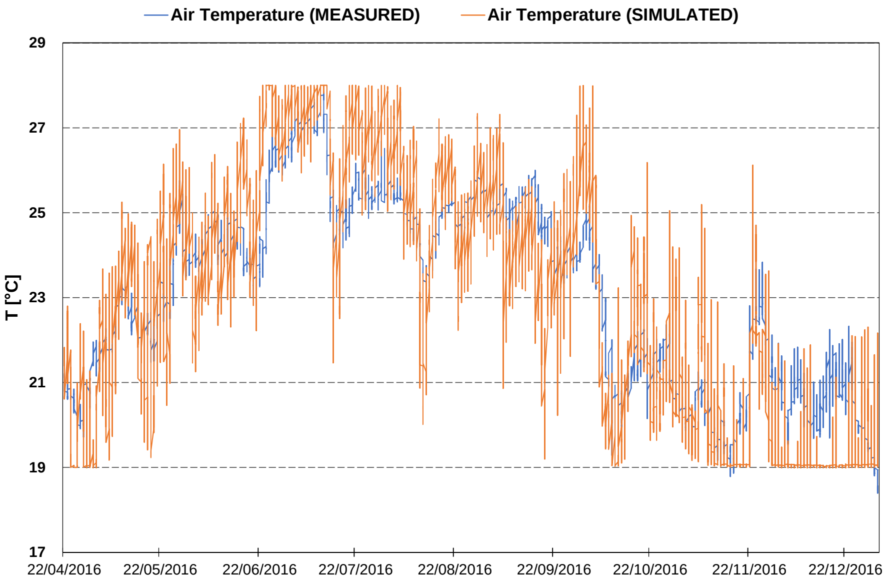

Figure 5. Comparison between monitored and simulated indoor temperatures for the bedroom

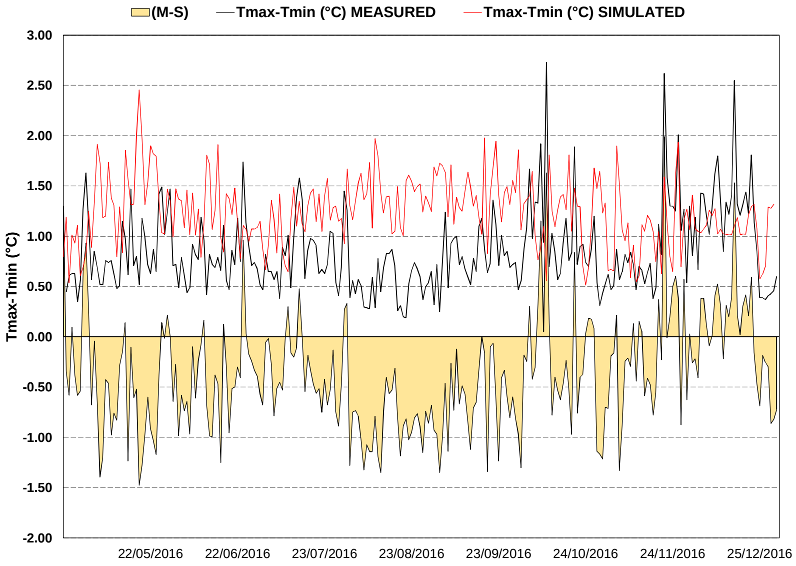

Figure 6. Daily difference between the maximum and minimum temperatures for the measured and simulated cases

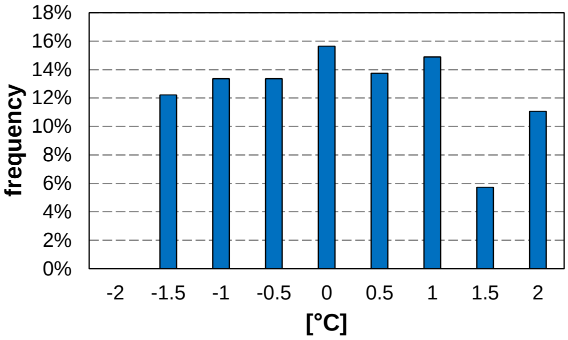

Figure 7. Frequency distribution of the daily average error

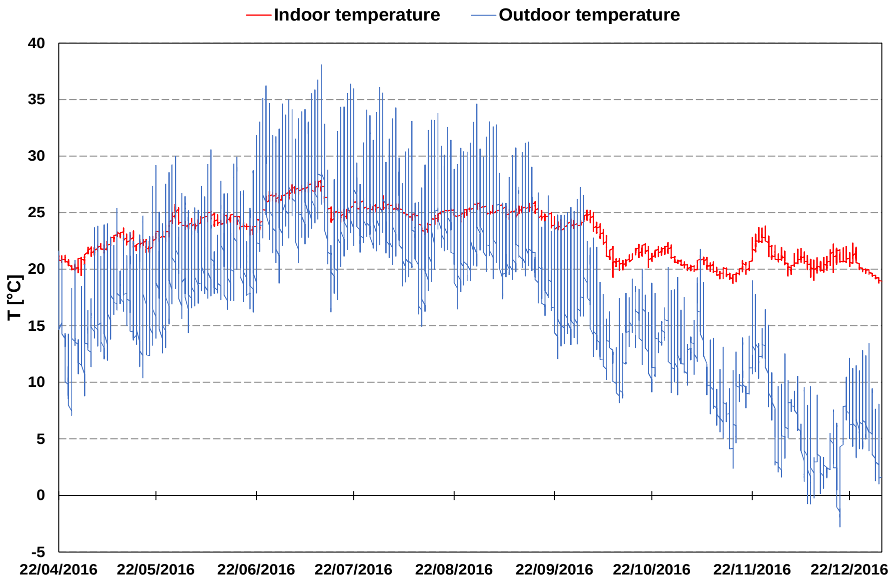

Figure 8. Indoor and outdoor temperature trends during the measurement campaign

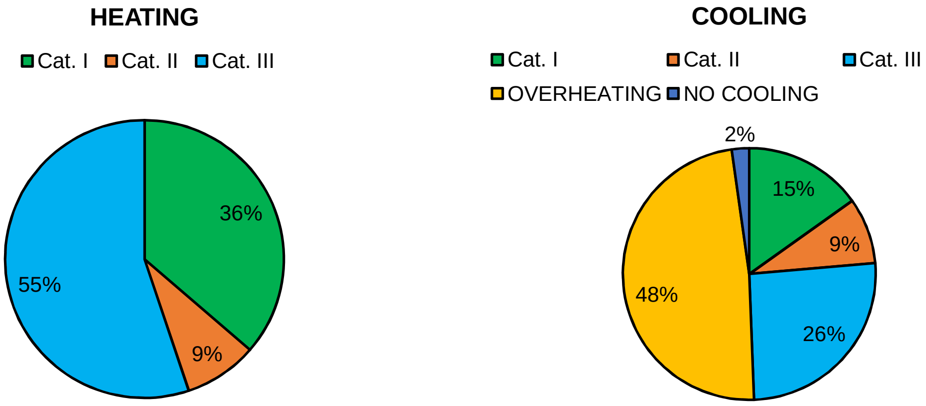

Figure 9. IEQ classes for indoor temperatures for the heating season (left side) and cooling season (right side)

- One-year monitoring campaign of IEQ parameters of a Passivhaus in Italy
- It is recorded good comfort in winter but overheating in summer for 50% of time
- Scenario analysis revealed insulation, windows and MVHR system should be changed
- With these changes, IEQ conditions are improved and overheating strongly reduced
- Economic savings as calculated by NPV over 30 years are 8775 euros for a flat