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Indoor quality-oriented approach for the performance evaluation of building retrofit with façade transformation: Case study of student dormitory in Mediterranean climate

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ABSTRACT

The rapid expanding of refurbishment incentives requires to deserve more attention on how to reach nearly zero energy standard without compromising occupant wellness, when the building is undergone to important architectural transformations. To overcome the above drawbacks mainly for student dormitories, the paper introduces a new indoor quality oriented post-retrofit evaluation approach that simultaneously quantifies the impact of design decisions on thermal, respiratory and visual comfort. Investigations on the building quality and readily monitored indoor variables are the core of the approach that also provides sensitivity analysis on some subjective parameters and questionnaires for the main involved stakeholders.

The proposed approach is tested on a student dormitory belonging at National and Kapodistrian University of Athens, refurbished in the frame of Horizon Project Pro-GET-OnE. The results reveal an improvement in the passive control of thermo-hygrometric comfort as well as in the satisfaction level. The adoption of mechanical ventilation consistently ensures dioxide emissions lower than 430 ppm, TVOC below 300 $\mu g/m^3$ and PM2.5 and PM10 lower than 6 $\mu g/m^3$. More in general, it is remarkable the importance of considering all comfort domains and occupant behavior, as one design or management choice might improve one indoor quality domain at the cost of others.

1. Introduction

The building sector is crucial for achieving the energy and environmental goals, at global level. In particular, extensive campaigns of building energy refurbishment are necessary in order to obtain strong near-term reductions in the greenhouse gas emissions of the civil sector. Another aspect has to be remarked: the incoming climate changes will negatively affect the energy and environmental performance of the existing old buildings, and this increase the importance of working on their sustainability and on the occupant's comfort [1,2] Taking into consideration these topics, in December 2021, the European Commission has proposed a revision of the Energy Performance of Buildings Directive (EPBD) [3]. The introduced approach is aimed to increase the rate of renovation, particularly for the worst-performing buildings making the existing stock more resilient and accessible. In the national implementation, it is also required to member states to take into account indoor microclimate not only in term of thermal comfort but also of air quality and global healthy level. Indeed, several studies have demonstrated that in North America and Europe, people spend 90 % of time indoors and kids tend to spend a little more time outside than adults. This phenomenon is increased starting from the Covid-19 pandemic and the diffusion of the smart-working. For this reason, the focus of international community has shifted on health and wellness inside the buildings by considering the environmental indoor quality (IEQ) that includes, among others, factors such as thermal comfort, air quality, lighting and acoustic comfort and damp conditions. Several aspects were investigated by the recent scientific literature both with experimental and numerical approaches with the aim to highlight the relation between the energy saving and the healthy state.

Focusing on the residential building sector, the available simulation studies are mainly focused on parametric or multi-objective evaluations.

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Nomenclature

BAL	Balcony
CO_2	Carbon dioxide emissions [ppm]
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
ER	Extra-room
g	Solar Factor
GET	inteGrated Efficient Technologies
HVAC	Heating, ventilation and air-conditioning system
IEQ	Indoor environmental quality
PM2.5	Particulate Matter with diameters lower than 2.5 μm [μg/m^3]
PM10	Particulate Matter with diameters lower than 10 μm [μg/m^3]
PMV	Predicted Mean Vote
PPD	Percentage of dissatisfied people [%]
RH	Relative humidity [%]
SET	Standard Effective Temperature [°C]
SS	Sun space
T_{db}	Dry-bulb air temperature [°C]
T_{MR}	Mean radiant temperature [°C]
T_{op}	Operative temperature [°C]
T_{set}	Set-point temperature [°C]
TVOC	Total volatile organic compounds [μg/m^3]
U_g	Glass thermal transmittance [W/m^2 K]
U	Thermal transmittance [W/m^2 K]
v	Air speed [m/s]

The main conclusion, for a large number of building-plans efficiency packages, is that also a basic refurbishment allows large energy savings with financial benefits [4]; at same time, a significant improvement was found within the ASHRAE-defined occupant comfort limits [5]. Ono et al. [6] have underlined that energy savings can be increased by more than 10 % with the control of the active system based on a suitable comfort model. With a cluster model of 54 buildings [7], it was also demonstrated that two rule-based room temperature controls could assure 22–27 % peak demand reduction compared to a regular operation. Ioannou et al [8] proposed a sensitivity analysis on the factors that affect the annual heating energy consumption and the PMV (predicted mean vote) comfort index according to ISO 7730 standard [9]. For the northern Europe climate, small variations in the metabolic rate, thermostat setting and clothing resistance caused very large PMV variation (up to 95 %). Underhill et al. [10], for a gas-heated midrise multifamily building in Boston, found that retrofits without ventilation or filtration measures led to an increment of the health costs due to higher PM2.5 concentrations (3.1 μg/m^3 and 20.4 μg/m^3 for standard and high-performance retrofits, respectively), basing on the ASHRAE 62.2standard [11].

More interesting and realistic information can be found from post-retrofit analysis; these investigate different aspects and more in general arrive to the conclusion that the energy saving measures should be selected without compromising the environmental indoor quality. Otherwise, a questionnaire survey mailed to 1550 owners of single-family houses in northern Sweden [12] suggested that energy cost reduction may not be the determining factor in deciding to undertake the building refurbishment; rather improving the indoor environment is more likely to be the reason.

More in detail, starting from post-occupancy evaluations, it was found that the materials added during the retrofits, such as sealants and insulation, can be sources of indoor air pollutants. For instance, thermal insulation materials [13], foam sealants and caulks [14] used to reduce uncontrolled air leakage, can emit a variety of volatile organic compound. Thermal insulation and windows replacement should make it easier to achieve and maintain acceptable thermal conditions [15] but according to Fisk et al. [16], indoor radon and formaldehyde concentrations tended to increase without the adoption of mechanical ventilation. Similarly, a study on multifamily residential buildings in Slovakia [17] indicated that occupants perceived the indoor air quality as better before renovation with slightly higher sick building syndrome symptoms since the reduction of air exchange rates have increased levels of formaldehyde and other volatile organic compounds. A survey on 154 buildings in the southern part of Switzerland (Canton Ticino), revealed the increment of radon concentrations, in particular where windows were replaced with more performant ones [18]. Monitoring the indoor conditions for three bed semi-detached co-operative social dwellings, Brodericket al. [19] confirmed the previous indications about the increment of some type of polluting substances due to lower building air exchange rates. Coggins et al. [20] basing on the survey of 14 retrofitted Irish residences, concluded that temperature and humidity in most homes were within design comfort limits meanwhile only 30 % of bedroom have CO_2 within 380 ppm of outdoor concentrations, suggesting that bedrooms maybe under ventilated. Median formaldehyde concentrations of 25.4 and 20.7 μg/m^3 were detected in bedroom and living rooms respectively, with building materials likely being the major source. Similarly, the in-situ measurements of Pungercar et al. [21] showed that the efficiency measures increased the indoor air temperature during the heating period by up to 2.5 °C, decreased relative humidity by up to 3.8 % and increased CO_2 by up to 24 ppm than before. Recart and Dossick [22] have also found that the retrofitted building envelope may suffer from higher levels of moisture and condensations risks that could also cause faster structural degradation. Data collected during long-term monitoring can reflect occupants' exposure to contaminants and can be used to suggest improvement in thermal comfort [23] according to standard of different countries. Furthermore, adequate ventilation [24], mitigation of indoor and outdoor pollution sources, and promotion of safe, low chemical emitting construction materials [25] during the refurbishment design are important to avoid potential negative impacts on the indoor environment and its occupants. A key strategy would be giving major attention to the design of the mechanical ventilation systems and their control strategy [26]. Few studies underline positive effects on IEQ; for instance, data collected from the occupants of 39 Finnish and 15 Lithuanian multifamily buildings both before and after energy retrofits indicated occupant satisfaction regarding indoor temperature and absence of upper respiratory symptoms [27]. Sarran et al. [28], through a questionnaire distributed to 2007 households in a social housing complex, found a general satisfaction with the indoor environment in retrofitted houses. However, occupants also expressed difficulties to understand and operate with the new heating and ventilation systems. The same problem was detected by Willand et al. [29]. The effectiveness of the retrofits was reduced by socially shared heating and ventilation practices that contradicted engineering assumptions. Starting form this reason, Colclough et al. [30] have justified the gap between the expected (<75 kWh/m^2y) and the actual performance, with some homes consuming more than twice the predicted energy. Moreover, it was found that poorly installed/commissioned heat pumps and lack of control (no external shading and window restrictors) can be the main causes of the worse performance [31]. A very recent study demonstrates that occupants of older houses show a deeper concern for energy renovation, due to the necessity of address aging systems and improve energy efficiency. Meanwhile, occupants of new houses tend to neglect system maintenance and monitoring [32].

All told, the studies based on the post-occupancy in the residential sector are usually focused on the measures of limited number of parameters or on questionnaires about people's attitude towards certain aspects of residential environment [33]. Most of the available monitoring campaigns regarded buildings undergone to traditional efficiency measures (mainly insulation and generation system replacement) without important architectural transformation, space re-functionalization or internal services addition. This causes a limited knowledge about the behavior of low-energy buildings after deep architectural and energetic refurbishment based on the analysis of all comfort aspects as well as in relation to the management strategies of new installed heating, ventilation and air-conditioning (HVAC) systems. Short periods of monitoring of indoor environmental conditions were commonly used and the resulting data may be not representative of the relation among the occupant's perception and the indoor environmental quality parameters; this is particular important when the structural or architectonic designs have applied important modifications of the living spaces. Moreover, analysis of the technical potential for energy efficiency often highlights very large comfort improvements considering traditional insulation measures with the same heated/cooled area; there are very few work focused on the effect of volumetric add-ons and the integration of higher glazed surfaces. Instead, these would be possible solutions implemented by the future architecture for increasing the livable space connecting occupants to outdoor environment with potential benefit in term of solar gains. On the other side, in warmer climate as the Mediterranean one, this aesthetical redesign could bring overheating phenomena with the increment of the cooling demand mainly when associated with wrong control of heat pumps and/or ventilation systems.

Furthermore, after the worldwide COVID-19 crisis, it becomes more important the control of contaminants also in residential building and in common living spaces where usually this aspect was demanded to natural ventilation. About this point, among residential uses, the student dormitories should be more deeply analyzed due to their special kind of use. These fall into the category of school buildings but the edifices are dedicated to ensure temporary stay (accommodation and meals) for students during their education program and thus these include both spaces for lecture activity that for residential use (bedrooms, public or private bathroom, kitchen, living rooms). Few studies have been developed for this special type of mixed private and public spaces and these are mainly focused on the analysis of the state of fact. This is the case of Sri Lankan university dormitories [34] for which it was found that opening windows on a regular basis may improve airflow. For the dormitories of a university in Shanghai [35], the results of subjective evaluation indicated mainly serious odour problems, especially during the period COVID-19 pandemic, with significant correlations between indoor concentrations of ammonia and air quality assessment. Briefly, the scientific literature is very poor of results or discussions about the refurbishment of these buildings and there are not works about post-retrofit analysis that take into account the different aspects of indoor environmental quality.

Here there are the novelties proposed by this paper: develop an indoor quality −oriented performance evaluation approach for the ex-post refurbishment analysis by means of readily monitored indoor environmental data and taking into account all stakeholders involved in the building utilization. The introduced approach can improve the post-occupancy management for the buildings undergone to important architectural redesign and efficiency measures on both passive control and active systems. The introduced approach was tested in the evaluation of the performance reached by the student dormitory of University of Athens; it has been interested by a deep energy refurbishment with volumetric add-ons in the frame of the European research project "Proactive synergy of integrated Efficient Technologies on buildings' Envelopes (Pro-GET-OnE)"—H2020-EE-2016–2017/H2020-EE-2016-PPP [36].

The new proposed approach is based on the monitoring of three levels of building environmental factors and sensitivity analysis on the parameters adopted by two different standards for the indoor environment classification the ASHRAE 55 [37] and the UNI EN 16798 [38]. Data about students' and administrators' perceived importance and satisfaction about the refurbishment action were collected by means of a survey. This new easy and complete framework will help researchers and designers to investigate the effect of innovative architectural solutions that realize the addition of new living spaces characterized by inteGrated Efficient Technologies (GET) and building services performance.

2. Case study

The case study is one building of the student dormitory of the National and Kapodistrian University of Athens within the University Campus of Zografou (37.97°N 23.76°E, Fig. 1a), about 5 km from the city center. Athens climate, Csa zone [39], is characterized by alternation between prolonged hot and dry summers and mild to cool winters with moderate rainfall.

The building (Fig. 1b, 1c), named "B FEPA", was built in 1986 and it is characterized by rectangular shape (56.6 m × 15.4 m) with four floors above ground and a basement. The overall gross building area is approximately 3642 m^2 and each floor (around 725 m^2) hosts 36 single-bed rooms for students, with the exception of the ground-floor, which hosts 30 rooms.

Following the criticalities highlighted by an extensive energy audit supported by a monitoring campaign, the building was undorgone to a deep energy refurbishment. All details about the state of fact and the adopted strategy for the energy retrofit design were described in detail in [40] and [41]. Briefly, the building skeleton was made of reinforced concrete not thermally insulated. The thermal conductance was not measured but all materials datasheets were made available by the technical office; thanks to these documents the stratigraphy of each envelope element has been created. Then, the calculation of the thermal transmittance (U) was done according to EN ISO 6946 [42] and it was found: 1.69 W/(m^2 K) for the external walls, 1.05 W/(m^2 K) for the roof and 2.07 W/(m^2 K) for the ground floor. Windows and glazed doors, not sealed, were made of single glass with aluminum frame; the glass thermal transmittance (U_g) was assumed equals to 5.9 W/(m^2 K) according to [43]. For the heating needs, the building was equipped with centralized gas boilers one with nominal power of approximately 988.6 kW and another one with nominal power of 732.7 kW, which provide the thermal vector fluid to in-room radiators and feed two newly installed storage tanks for hot water production. There was no central air conditioning system with the exception of few rooms with autonomous split systems. Regarding the lighting system, the dormitory was equipped with fluorescent lamps (average efficiency 60 lm/Watt), with a total installed power of 26.5 kW in the rooms and 18.7 kW for common spaces.

The refurbishment was aimed to integrate the combination of the innovative energy and environmental technologies in a specific architectural design based on the remodeling of glass facades for increasing the living design taking into account user's satisfaction, building quality, aesthetics, and internal functionality. Thus, the basic action has been the application of a steel structure with portals on the main sides of the building connected to the existing concrete structure at the nodes and equipped with bracing systems. The developed exoskeleton provides the building with seismic strengthening and energy efficiency, and facilitates the final design of the additional space for each bedroom. Finally, the net conditioned building area has increased from 2584 m^2 to 2681 m^2 and for instance, the net floor area of a typical bedroom is passed from 9.50 m^2 to 23 m^2 with one glazed surface of 2.7 m^2. The main efficiency measures have regarded:

– building envelope: the addition of 6–10 cm of insulation has allowed U value of 0.29 W/(m^2K) for wall, 0.29 W/(m^2K) for the ground floor and of 0.28 W/(m^2K) for the roof, moreover windows with aluminum frame with thermal break and double glasses (U_g = 1.7 W/m^2K) with

Fig. 1. Location (a), aerial view (b) and façade (c) of the building under investigation.

a Solar Factor (g) of 0.57 and a Light Transmission of 0.75 were installed;

– active system: a centralized mixed air–water system was installed consisting of four air-to-water heat pumps (HP), one for each floor, characterized by a Coefficient of Performance (COP) of 3.20 and by an Energy Efficiency Ratio (EER) of 2.95. The electric HP is connected to each room through 2 pipe Fan Coil Units (FCU), with a constant water flow and variable speed fan. The HPs are also connected to two water storages with a capacity of 500 l. In each zone, a decentralized mechanical ventilation system, equipped with sensible and latent heat recovery and air filtration, can provide five different fresh air flows with a relative efficiency up to 82 %. A triple filter eliminates particulate matter (up to 98 % of PM2.5 and all PM10), together with pollen, dust mites, spores, and bacteria larger than 0.4 μm. Moreover, four autonomous systems were installed in two double rooms on the ground floor and on the first floor. Those air-to-air HPs have nominal heating power of 3.18 kW and COP of 3.8, nominal cooling power of 2.14 kW and EER of 2.95. These are equipped with an electronic filter (efficiency 90 %, according to ISO 16890) and an active thermo-dynamic heat recovery with a total flow air provided to each room of 400 m^3/h;
– renewable energy systems: PV strings with a total power of 14.4 kW_p were installed on the rooftop with a tilt angle of 35° and also a solar collector system (38 panels), south exposed, with 45° tilt;
– replacement of the electrical equipment and lighting system.

3. Method for student's dormitory post-retrofit analysis

As also underlined by the literature [44], post-retrofit analysis of dormitories can show that tenants and owners are often in disagreement on how, when and why a building should be adequately refurbished mainly when invasive interventions are programmed with also modification of livable spaces. On the other hand, the occupants are a largely untapped source of information for facility managers, interested in improving the performance of their buildings.

In this frame, the paper introduces a new complete method that based on the identification of correlations between occupant satisfaction, measured data and technical attributes of building systems allows evaluating the improvement of indoor environmental quality. This method employs a practical two-step procedure that combines objective analyses of quantitative measures with self-friendly equipment and subjective investigations such as surveys about the perception of indoor environmental quality of occupants and managers.

The method can be transformed into a design-supporting tool for the design of dormitories refurbishment because, more in general, it allows to identify the key factors for the built environment optimization and to correct problematic behaviors about the management of passive and active systems that bring performances below expectations. About the practical application, the method can support designers and researchers for implementing data-driven design strategies focused on the indoor quality and for reducing the technical obstacle to the sustainable refurbishment.

3.1. General description of method

Fig. 2 schematizes the proposed approach. More in detail, when the building was undergone to a deep architectural and engineering refurbishments, it is important a global overview of the qualitative obtained improvement by means of the infrared thermography. It is a non-destructive contactless technique that makes possible to compare thermal in-homogeneities of opaque and glazed elements before and after the intervention. The prescriptions of UNI EN 13187 [45] standard must be followed; calibrating the camera by means of the surface temperature measured with contact thermometer.

Then, the approach implements quantitative measures of the main variables for describing the environmental factors under investigations. The first considered aspect is the thermo-hygrometric comfort that, according to some studies [46], has greater influence on occupant's overall satisfaction compared with visual, acoustic and respiratory health. According to ASHARE 55 [37] and UNI EN ISO 7730 [47] standards, thermal comfort intends "a condition of mind that expresses satisfaction with the thermal environment in which it is located". Moreover, hygrometric aspects are connected to the level of relative humidity that also affects the human body transpiration exchange. The evaluation of these aspects requires the measurement of all parameters needed for the calculation of the operative temperature (T_{op}) and the global thermal comfort indices, PMV (Predicted Mean Vote) and PPD (Predicted Percent Dissatisfied).

Specifically, dry-bulb air temperature (T_{db}), air speed (v), relative humidity (RH) and mean radiant temperature (T_{MR}) must be monitored with sub-hourly time step (for 1 to 30 min) in the most representative environments. According to [47], for low air velocity ($v < 0.2$ m/s) and small temperature difference $|T_{db} - T_{MR}|$, the operative temperature is the arithmetic mean:

$$T_{op} = (T_{MR} + T_{db})/2 \tag{1}$$

The calculation of PMV and PPD requires the knowledge of metabolic rate and clothing insulation; these parameters can vary the results of global comfort evaluation and should be detected by means of continuous survey or these should be varied by means of a sensitivity analysis. Moreover, when the room is equipped with an active system the indoor conditions strictly depend by the management strategy that can affect both temperature then relative humidity. With the aim to understand what strategy can both minimize the energy consumptions and optimize the indoor thermo-hygrometric conditions a sensitivity analysis could be conducted by varying the set-point temperature (T_{set}) and by studying the effect in relation with adopted retrofit measures.

About the threshold values, considering the indoor environmental classes (from I to IV) of the reference standard [38] where class II indicates the normal level of expectation that should be used for new buildings and renovations, Table 1 reports the values to be considered for the analysis. More in detail, the standard provides graphical and analytical comfort zone methods for a wide range of input parameters such as air speeds and humidity. In Table 1, the range for the operative

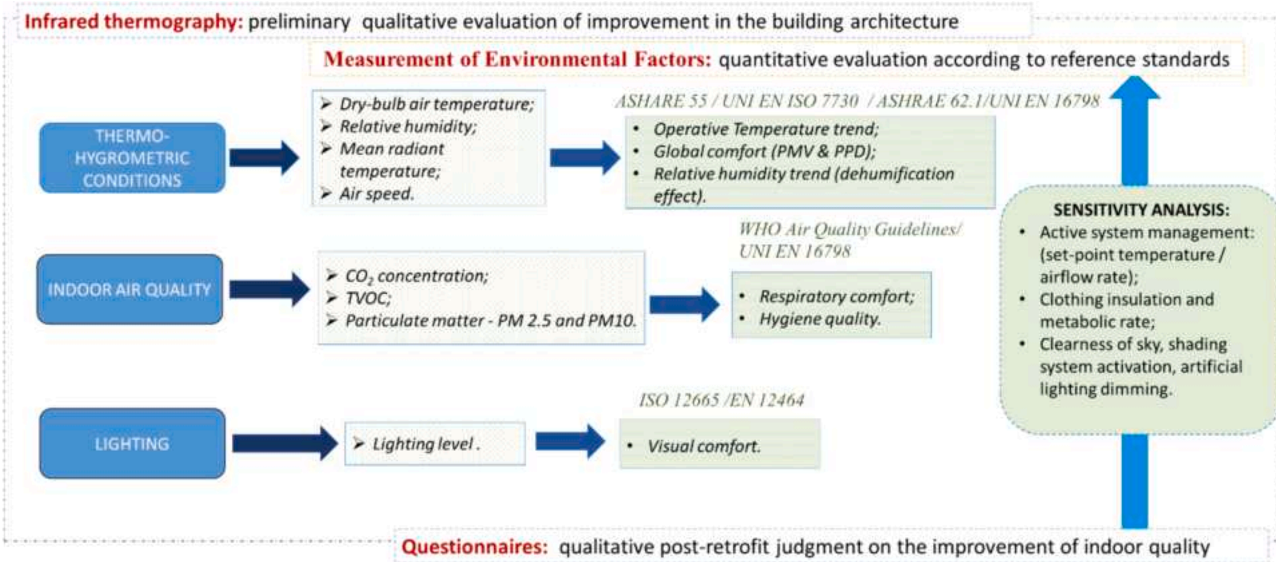

Fig. 2. Approach for post-retrofit dormitories analysis.

Table 1
Limits for the indoor parameter according to UNI EN 16798 [38].

Category	PPD	PMV	T_{op} [°C]		RH [%]	v [m/s]	
			winter	summer		winter	summer
I	<6%	−0.2 < PMV<+0.2	21.0–25.0	23.5–25.5	30–50	0.10	0.12
II	<10 %	−0.5 < PMV<+0.5	20.0–25.0	23.0–26.0	25–60	0.16	0.19
III	<15 %	−0.7 < PMV<+0.7	18.0–25.0	22.0–27.0	20–70	0.21	0.24
IV	<25 %	−1.0 < PMV<+1.0	17.0–25.0	21.0–28.0	–		

temperatures is referred to clothing of about 1.0 clo in winter and 0.5 clo in summer, sedentary activity (1.2 met), RH equals to 40 % and 60 % respectively in winter and summer, v < 0.1 m/s. In the same operative conditions, according to ASHRAE 55, for the summer the optimal range is 24–27 °C and for the winter it is 20.5–24.5 °C; the acceptable PMV ranges between −0.5 to + 0.5 that corresponds to PPD of 10 %.

Finally, Table 1 shows the maximum air velocity as reported in [38] for avoiding thermal discomfort; these values are referred to an activity level of 1.2 met, turbulence intensity of 40 % and T_{db} of around 20 °C in winter and 23 °C in summer; in this case when T_{db} rises up 25 °C, higher values can be accepted until 1.2 m/s for temperature around 27.2 °C.

Understanding and controlling common indoor pollutants can help to reduce risk of indoor health, improving the so-called respiratory comfort. Based on ASHRAE 62.1, as acceptable indoor air quality is defined the "air in which there are no known contaminants at harmful concentrations as determined by authorities and with which a substantial majority (80 % or more) of the people exposed do not express dissatisfaction" [11]. Indoor air quality must consider a lot of variable but a post-retrofit analysis can be focused at least on carbon dioxide (CO_2), PM10, PM2.5 and total volatile organic compounds (TVOC). For this aspect, the sensitivity analysis could regard the variation of airflow rate of the mechanical system; otherwise the results with natural and mechanical ventilation have to be compared for giving occupants the freedom to act on the windows.

The reference values for CO_2 concentration above the outdoor one are given by [38] with reference of kind of use. Considering the bedroom as the main one in the student's dormitory, Table 2 shows the limit values.

Table 3 shows the limitations applied to the TVOC concentration according to which it is possible to define a building as low or very low polluted [48].

Instead, Table 4 reports the average values allowed for the concentrations of PM10 and PM2.5 on a daily basis (24 h) [48].

Table 2
Design ΔCO_2 in bedroom.

Category	ΔCO_2 concentration for bedrooms (ppm above outdoors)
I	380
II	550
III	950
IV	>950

Table 3
Criteria for TVOC concentration.

SOURCE	Low emitting products for low polluted buildings	Very low emitting products for very low polluted buildings
TVOC	<1000 μg/m^3	<300 μg/m^3

Table 4
WHO health-based criteria for indoor air.

Pollutant	WHO – Air quality guidelines
Particulate matter PM 2.5	24 h mean: 25 μg/m^3 Annual mean: 10 μg/m^3
Particulate matter PM 10	24 h mean: 50 μg/m^3 Annual mean: 20 μg/m^3

As regard the third aspect, the standard ISO 12665 defines visual comfort as "a subjective condition of visual well-being induced by the visual environment" [49]. A good state ensures that people have sufficient light for the activities or tasks they are engaged in; over-lighting or under-lighting would cause human visual discomfort. Thus, lighting measurements should be carried out in different conditions of sky (clear, partially cloudy, cloudy) in order to evaluate both natural and artificial lighting contributes. A sensitivity analysis could be performed by considering the adoption with different schedules of the installed shading system and the modulation of artificial light (if possible) in the most representative hours of all seasons. A map of the room occurs for deciding the most representative points for measuring the lighting level with short time step (e.g. 5 min). For the quantitative evaluation, the uses comparable to residential one have not strict values; the EN 12464–1 standard [50] can be used and it indicates both for offices and educations the range 500–1000 lux.

Finally, a satisfaction survey must be developed based on the scope of the renovation actions. The reference could be the work of Hou et al. (2020) [51] that have developed a questionnaire which was divided into three sections:

- the first part inquires student's personal particulars, including their gender, room type, length of inhabitation period and fraction of time they stayed in the room;
- secondly the questionnaire invites students to indicate their levels of expectation and satisfaction on each building performance aspect (visual comfort, thermal comfort, aural comfort, fire safety, hygiene, communication via information technology);
- the third part asks them to indicate their perceived relative importance between pairs of the building's performance aspects, in order to illustrate the individual respondent's explicit preference for the items under consideration.

More in general, the questionnaires should be easy and quick to fill in as well as user-friendly (approximately 5–15 min' maximum). Thus, they are composed mainly by direct questions in which, the user has to estimate a score on a 5 or 7 points grading scale, as numerous publications report [52]. Sometimes questionnaires also contain a final section in which the user can provide more qualitative answers (open questions) in order to cover issues which were not included/answered in the listed questions [53].

Starting from these examples, it is introduced a questionnaire divided into two parts. The first part contains 31 questions for administrators and site managers/engineers and the second part 31 questions for users and occupants. In both parts, it is asked to rate the current performance of the refurbished building, regarding four main fields:

- User's comfort (thermal, visual, living space, managing of bioclimatic environment, ventilation, acoustic, etc.).
- Sustainability aspects (thermal insulation, plants powered by renewable energy sources, materials, etc.).
- Technical aspects (seismic safety, evacuation plan, fire safety, etc.).
- Social aspect (benefits to the whole urban district, aesthetics, etc.).

Satisfaction level is rated on a scale from 1 to 5, where 1 corresponds to "very dissatisfactory" and 5 corresponds to "very satisfactory". Moreover, a sixth option, namely "I can't evaluate" is available. The questionnaires end with four open questions referring to the four main subjects, as suggested by the literature overview.

3.2. Details for the application to the case study

The approach is applied for the post-retrofit analysis of B FEPA building which refurbishment was completed at September 2022. Fig. 3 shows the comparison between the plants of ground floor before and after the refurbishment and also the pictures of the building during the refurbishment. The GET system assures Extra-Room (ER) on the ground floor, Sun-Space (SS) on the other floors and Balcony (BAL) for all floors.

The qualitative phase of proposed approach has regarded the whole design, meanwhile the application of quantitative measures is started in the final part of the project and it has regarded a double bedroom

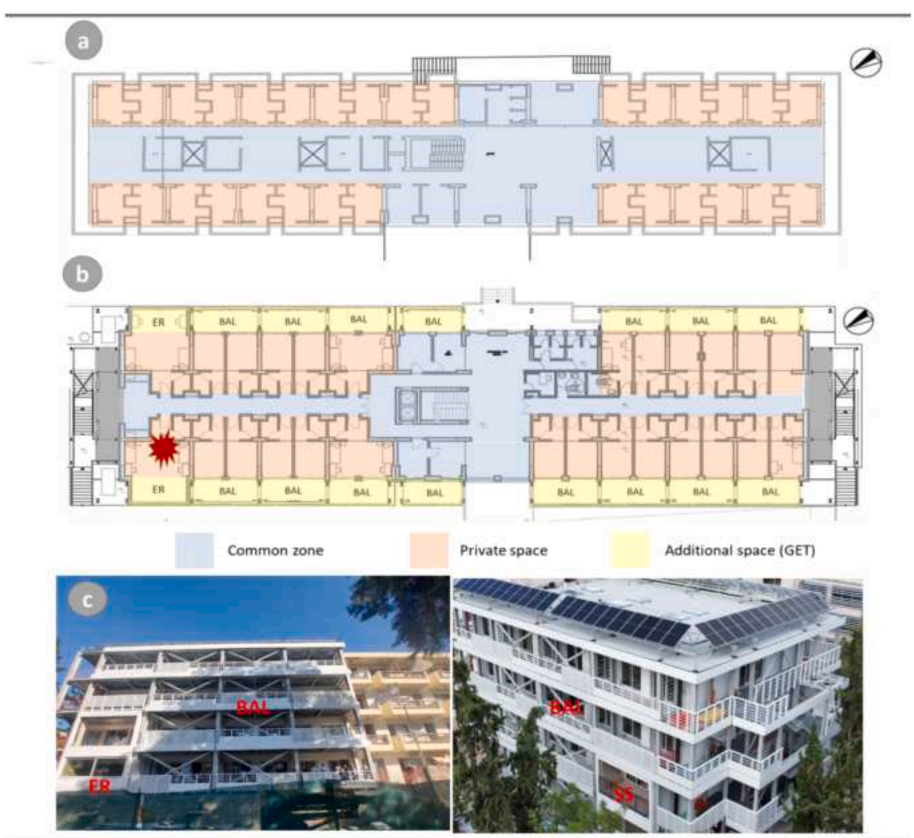

Fig. 3. Plans of the ground floor, before (a) and after (b) the renovation; c) Renovated building real image.

located in the Northwest side of the building, at the ground floor (Fig. 3b). The room has a gross area of about 15 m^2 and is occupied by two students. The transparent surface is approximately 2 m^2 and it is served by one of the autonomous air-to-air HP. IAQ Tongdy sensors (TSP-18) consisting of portable continuous recording equipment were used for measuring simultaneously: dry-bulb air temperature, relative humidity, concentrations of carbon dioxide, PM10, PM2.5 and TVOC. It was installed inside the bedroom in the wall near the bed avoiding the incidence of direct solar radiation. The CO_2 recording range is from 0 to 2000 ppm with accuracy of ± 40 ppm at 25 °C and for the TVOC from 1 to 30 ppm with accuracy of 1 ppm. The measuring ranges for temperature and RH are 0 to 50 ℃ and 0 to 95 % (non − condensing) and for PM2.5 and PM10 are 0–500 μg/m^3 with accuracy respectively of ± 2 μg/m^3 + 15 % and ± 2 μg/m^3 + 20 %. Moreover, the mean radiant temperature was obtained by means of a black globe thermometer with Tolerances Class 1 and recording range from 0 °C to 80 °C which datalogger integrates the equations proposed in the standard ISO 7726 [54]. The air speed was measured by means of a hot wire anemometer with measurement range 0–5 m/s and accuracy of ± 0.03 m/s. These two sensors were placed on a pedestal at a height of 1.50 m from the floor level. This height is reasonable for evaluating the thermal wave and air movement as consequence of climatic perturbations, considering standing people as well as seated persons.

All parameters were continuously recorded with 5 min' time-step. Quality assurance of the equipment used was performed in several occasions and all instruments were calibrated according to the manufacturers' standards.

More in detail, the monitoring data are available from 13 September 2022 to the end of May 2023. The starting date depends by the end of the retrofit works meanwhile the summer months (June and July 2023) would be characterized by discontinuous occupation due to exam session and holyday and it was decided to interrupt the monitoring for a first step of evaluation. Further monitoring campaigns are under evaluation for checking the performance in different rooms and for the most critical outdoor condition. Moreover, during the pre-retrofit phase the building was undergone to a long monitoring (from April 2018 to March 2019) of the same variables but in the common area of all floors as detailed in [55].

The following table summarizes the average and extreme monitored values considering three reference seasons that will be used for the comparison with the post-retrofit monitored variables. More in general it can be observed a poor control of indoor variable, mainly during intermediate and summer season also due to absence of ventilation and cooling services.

For evaluating visual comfort, the Illuminance TES 1335 Light meter has been adopted with measurement range 0–400 klux and accuracy of ± 3 %. The luxmeter was always placed at the height of the work surface (80 cm). The monitoring was not in continuous but with acquisition time of 5 min and the acquired average value (Lux) was considered. In detail, among the available measures in the following section the most representatives were discussed:

(1) from 8:00 to 10:00 of September 21st: cloudy sky, lighting system off and window shielding systems not applied;
(2) from 13:00 to 15:00 September 22nd – clear sky, lighting system on and window shading systems not applied;
(3) from 17:00 to 19:00 September 23rd: lighting system on and window shading systems applied.

About the thermo-hygrometric comfort and indoor air quality, it is proposed a daily analysis focused on the first week of activation of the new installed HP. This study was developed during the project according to the intent of demonstration site activities. Then a global analysis is developed based on data monitored from 21st September 2022 to July 2023.

More in detail for the daily analysis, the heat pump was activated from 15th to 20th September 2022 at 9:00 with the following schedule decided by occupants according to their preference:

- September 15th-16th − Sub-period 1 (S1): T_{set} = 25 °C;
- September 17th – 18th − Sub-period 2 (S2): T_{set} = 24 °C;
- September 19th-20th − Sub-period 3 (S3): T_{set} = 23 °C.

During these days, it was also asked to the occupants to declare their activity and clothing. For the global analysis, the instruments have continued to record the same variables but the occupants have autonomously set the heat pump operating mode, and there was not information about activity and clothing. However, the acquired data were subdivided into three mainly period: the winter (subscript *win*, 1st November – 31st March) with the heat pump activated in heating and ventilation mode; the summer (subscript *sum*, 1st May − 30th September) with the heat pump activated in cooling and ventilation mode; the intermediate seasons (subscript *as*, April and October) with only the ventilation service. A sensitivity analysis was developed by varying the clothing insulation parameter when the global comfort indices were calculated; the study is also divided into nocturnal (from 21:00 to 9:00) and diurnal hours and taking into consideration a metabolic rate of 1.0 met.

The questionnaire introduced in the previous section and consultable at the project webpage [36] was submitted at the end of works in September 2022. Among the acquired information, there is the time during which the students have lived in the building as well as the type of room they occupied (single/double room). Similarly, the site managers should state the time they have handled the building. Briefly, the questionnaire is focused on the vote assigned to all comfort domains but also on the perceived seismic safety and energy efficiency level, on the satisfaction about new livable spaces and aesthetical features as well as on the impact of the refurbished building on the urban aspect/landscape and the social life of the university campus.

4. Results for the case study

4.1. Qualitative evaluation of architectural design

Following the proposed approach, a global infrared thermography was done for qualitatively evaluating the effects of the energy retrofit in terms of reduction of heat loss and air tightness. The investigation was done during several days both on the state of art and on the refurbished building for obtaining comparable external and internal conditions. The thermal camera, *AGEMA* THERMOVISION 570 (accuracy ± 2 % of range or ± 2 °C, thermal sensitivity < 0.15 °C, spectral range between 7.5–13 μm) was used. In order to avoid thermal anomalies, the following conditions were taken into account, according to [43]:

- surfaces free from direct solar radiation for at least one hour before the survey;
- no precipitation either just prior and during the survey;
- dry building surfaces;
- wind speed less than 10 m/s during the operation.

Fig. 4 compares the thermo-graphs for two days during which the average outdoor temperature during the measures was varied between 15–16 °C; the sky was partially cloudy with a sky's clearness index evaluated according to the procedure of Kudish et Evseev [56] between 35–65 % for all measurement period; wind speed and direction between 0.51 and 0.6 m/s and prevalent east direction; last precipitation 6 days before.

The effects of higher thermal insulation are remarkable. First of all, it can be observed a greater uniformity of the temperature both for the external facades (Fig. 4a) and the roof (Fig. 4b); this implies a reduction of conductive heat flows and of thermal losses through thermal bridges, which account for a large part of the additional energy load of the

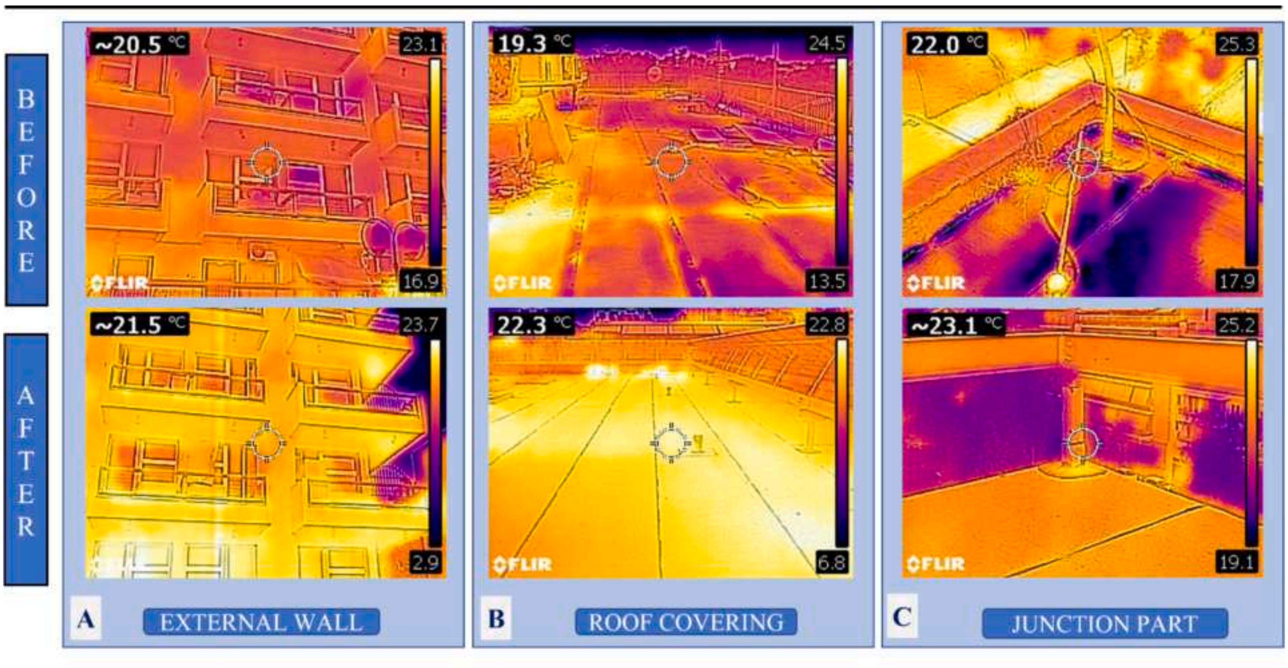

Fig. 4. Thermal scanning outputs, before and after retrofit comparison: a) external facade; b) roof; c) junction part.

building before the refurbishment.

In particular, the picture shows the resolution of the thermal bridges due to the window frames (Fig. 4a) and the junction parts, as an example those located on the corner of walls or between wall and roof (Fig. 4c). These improvements positively affect the passive control of indoor conditions that contribute to reduce the activation of heating and cooling system.

4.2. Quantitative evaluation of environmental factors

4.2.1. Thermo-hygrometric comfort

Fig. 5 shows the trend of the operative temperature recorded on the first day of indoor monitoring after the refurbishment, when the cooling system was turned off. During the night and until the 7:00 in the morning, there is no need to cool the room, due to favorable outdoor conditions since the air temperature varies from 17 °C to 26 °C and the relative humidity from 47 % ad 71 %. However also when the external conditions are more severe, T_{op} is inside the comfort zone suggested by ASHRAE 55 standard (reported as lower and upper limits). Indeed, from 8:00 to 16:00 the outdoor temperature is always higher than 26 °C with peak value of 31 °C (at 11:00) when the solar radiation is 706 W/m^2; under these conditions, the building envelope assures good resilience. Only from 17:00 to 19:00, T_{op} is above the upper limit, with an average value of 28 °C. This underlines that also with higher glazed surface, the design does not cause overheating problem. Indeed, since the cooling system is turned off, the control of solar gains is achieved only with the passive adopted efficiency measures that assure higher thermal inertia and insulation level as also underlined in the following analysis.

Fig. 5 also suggests that the difference between the temperature inside the building and outside, is higher than the one verified for the pre-retrofit configuration and the passive control of the indoor condition was being optimized. Indeed, the pre-retrofit monitoring has shown that during the cooling season, the indoor and outdoor temperature values were comparable. In detail, for the rooms at ground floor, the indoor temperature was varied from 29.7 °C to 22.6 °C with an average monthly value of 26.5 °C.

Fig. 6 shows the trend of operative temperature when the cooling system is turned on and different set-point temperatures are considered. The three sub-periods (S1, S2 and S3) are indicated with different colors, but in general, T_{op} is lower compared to the previous day; in detail the average daily value is 24.4 °C, 23.2 °C and 22.5 °C respectively during S1, S2 and S3 meanwhile the outdoor conditions are comparable with an average daily outdoor temperature near 26 °C and peak values between 30 °C or 33 °C. During S1, the operative temperature is usually inside the comfort zone (79 % of monitoring time) considering the ASHRAE standard, and it never exceeds 26 °C. The late afternoon is the most

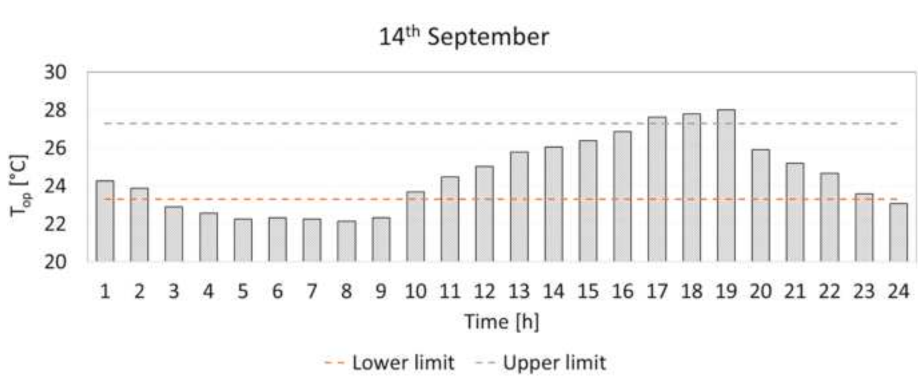

Fig. 5. Operative temperature trend in the first day of monitoring period.

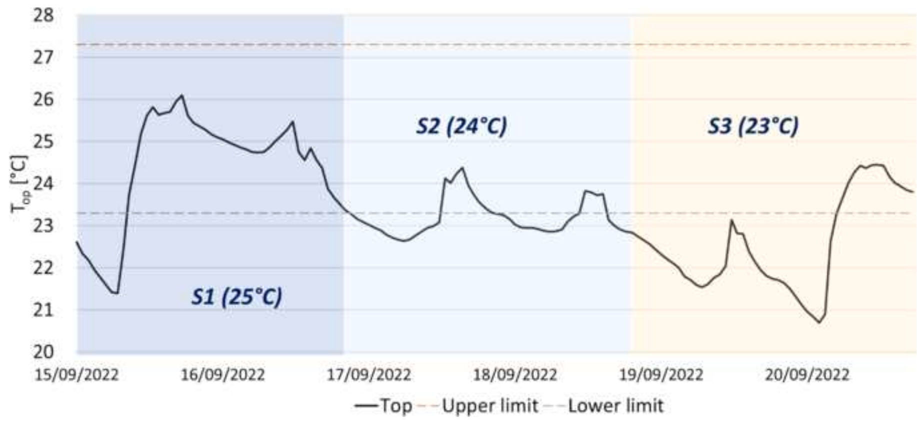

Fig. 6. Operative temperature trend in S1, S2 and S3.

critical period because also if the outside temperature is not high (near 23 °C), the solar gains stored by the GET system are discharged inside the room. The same trend is found in S2 but the average value of the operative temperature is low due to selected set-point, and it is frequently under the lower limit. T_{op} is in the comfort zone only during the late afternoon when there is the inertial contribute of the building envelope since during the outdoor temperature varies from 33.3 °C (12:00) and 26.5 °C (16:00) and the solar radiation is higher than 650 W/m^2. With the last management strategy selected by occupants, the operative temperature is not comfortable for the analyzed standard and it becomes higher than 24 °C only during the late afternoon for the same reasons of the other sub-periods. Both in S2 an S3 only the 27 % of values are inside the comfort zone.

Furthermore, according to Table 1, during S1, the operative temperature is mainly in the I category (60 %) and this assures that the selected set-point can bring satisfying conditions. With a set-point of 24 °C, the hourly values of T_{op} are inside category III for 46 % of time meanwhile, for the last sub-period, the percentages of hours in categories I, III and IV are comparable, with an average value of 32 %.

Fig. 7 shows the distribution of the operative temperature in the other monitored periods. First of all, it indicates that during the summer the occupants have chosen very low values for the set-point temperature, as also verified during the previous daily analysis and this brings to very low average values for T_{op}, most commonly in the range 22–23.5 °C. These values can be compared with the ones of pre-retrofitted building previously proposed in Table 5. The improvement is clear: the maximum recorded temperatures differ of around 7 °C and the average values of around 5 °C.

In the winter months, the most frequent set-points would be around 20–21 °C since the operative temperature ranges commonly between 20–21.6 °C. The highest recorded T_o is lower than in the pre-retrofit case and this indicates a good passive control of the installed glazed systems. These have been recorded in both cases during the month of March, when the outdoor conditions are usually very mild and the solar gains increases. On the other side, the insulation and the reduction of air-leakage allow minimizing the heat losses; thus the minimum value does not go currently below 19 °C meanwhile in the pre-retrofitted case it was near 14 °C.

In the intermediate seasons, there are the most variable conditions with the highest value near 28 °C. It is recorded at the end of April due to higher solar gains than in the pre-retrofitted case characterized by maximum value of 25.4 °C. However, this could be a local phenomenon because the occupants did not active the internals screens or due to higher internal loads.

Fig. 8 shows the percentage of values that falls into the comfort category according to UNI EN 16798 standard and the comparison with the acceptability range considered in the ASHRAE 55 standard. Also this analysis confirms that the indoor control during the winter season is optimal because for around 80 % of values the Category II is achievable according to UNI EN 16798 standard and the range proposed by ASHRAE is satisfied. Instead the summer season could be interested by management optimization since the 63 % of values fall within Category II; this percentage becomes 25 % when ASHRAE standard is considered. This happens because the recorded temperature goes down the lower limits proposed in Table 1.

All told, these data suggest that the adoption of low set-points is not advisable according to the current standard; thus, also if occupants prefer to select extreme management strategy to front overheating sensations, this choice is not adequate for a good classification of the indoor environment in term of thermal comfort.

Relative humidity shows a very stable trend (Fig. 9) with an average value of about 48 % in the summer and around 41–43 % in the other

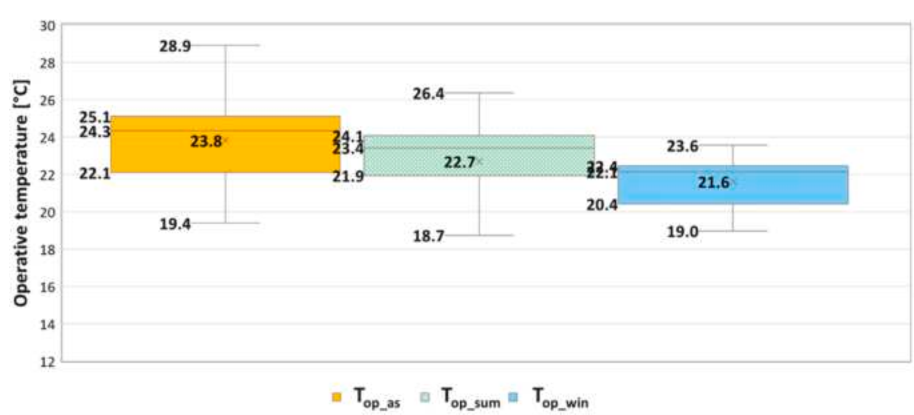

Fig. 7. Operative temperature distribution in the monitored period.

Table 5
Average and maximum values monitored in the common area of ground-floor before the retrofit.

	RH [%]			To [°C]			CO_2 [ppm]		TVOC [μg/m^3]	
	Average	Max	Min	Average	Max	Min	Average	Max	Average	Max
Winter	39.1	66.8	22.7	20.5	26.5	14.1	469	799	892	1518
Spring-Autumn	44.0	67.0	25.8	22.0	25.4	14.41	471	608	586	1638
Summer	43.2	71.6	23.4	27.2	33.2	17.6	466	668	421	1688

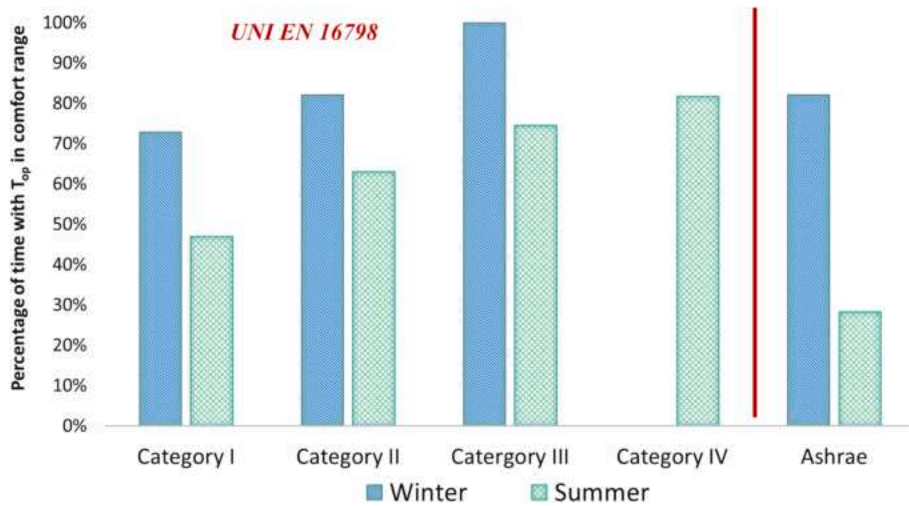

Fig. 8. Operative temperature in comfort zone according to UNI EN 16798 and ASHRAE 55.

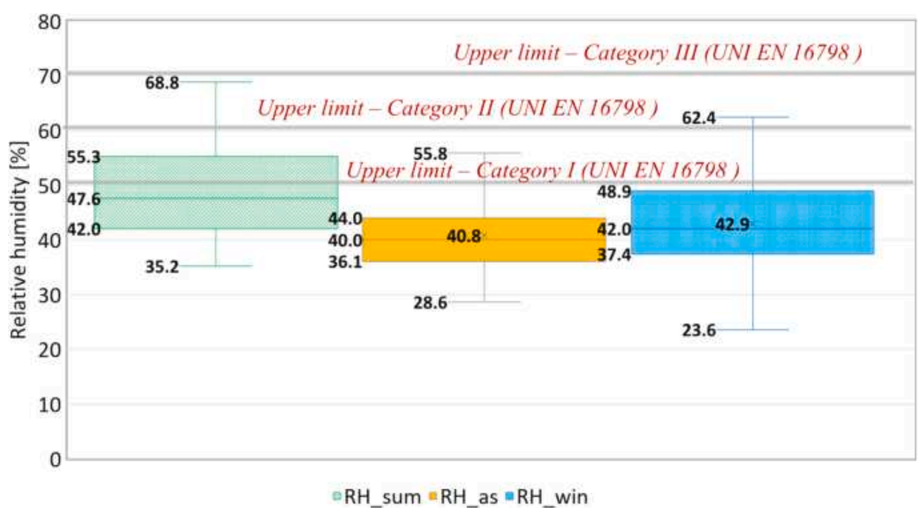

Fig. 9. Relative humidity distribution in the monitored period.

seasons. In general, the RH levels are always under the upper limit for category III and these are most commonly in category II. Indeed, taking into consideration both upper and lower limits considered in Table 1, for the intermediate seasons, the category II is always achievable, and in 90 % of cases also the Category I. In the other seasons, for more than 95 % of the measures, the category II is achievable.

The analysis developed for the initial days confirms the previous general results. Indeed, in the sub-periods S1 and S2, the levels observed are comparable and higher, with an average RH equals to 55 % and an average percentage of hours in category II equal to 91 %.

More in general, the adoption of ventilation and air-conditioning system assures more stable conditions compared to the state of fact. For instance, during September 2018, the monitored RH was varied between 29.5 % and 64.3 % with an average value of 41.7 %. Briefly, as shown, in Table 5 in all seasons there are more extreme values.

The comfort sensation was also evaluated by means of the calculation of global comfort indicators but the results can be really different according to the adopted level of clothing also if all monitored environmental variables are used for the calculation. During the first monitoring week, the students have specified different clothing preference:

- Trousers, long-sleeve shirt (0.61 clo) – main clothing type;
- Knee-lenght skirt/shorts, short-sleeve shirt, sandals, underwear (0.54 clo);
- Trousers, short-sleeve shirt, sandals, underwear (0.57 clo);
- Knee-lenght skirt, short-sleeve shirt, sandals, full-slip (0.67 clo);
- Sweat pants, long-sleeve sweatshirt (0.74 clo).

Thus, for the following analysis of summer period, it is considered:

- Low insulation clothing: 0.5 clo;
- Medium insulation clothing: 0.6 clo (reference value);
- High insulation clothing: 0.7 clo.

For the winter months, the assumed values are:

- Low insulation clothing: 0.6 clo;
- Medium insulation clothing: 0.8 clo;
- High insulation clothing: 1.0 clo (reference value).

Figs. 10, 11 and 12 show the PMV and PPD values in the three examined sub-periods only for the diurnal period. These results refer to clothing resistance of 0.6 clo. Globally, during S1, the PMV is between −0.66 and + 0.28 and the PPD varies between 5 % and 8 % and thus the conditions required by ASHRAE 55 standard are verified in almost all considered hours meanwhile the PMV and PPD values fall into category II. During September 16th, with the assumed values of the other variables, the comfort indices are mainly in category I and only during the evening more severe conditions are reached also if the trend of operative temperature was good.

In the second sub-period (Fig. 11) the indoor parameters are much less favorable to thermal comfort. Indeed, during September 17th, the PMV shows a minimum value of −0.99 at 9:00 and a maximum value of −0.26 at 18:00 on the same day. At these values, the PPD is equal to 26 % (PPD max) and 6 % (PPD min), respectively. The comfort indices are in category IV for 63 % of hours and these are acceptable for 23 % of time according to ASHRAE 55.

Finally, in the last sub-period (Fig. 12) until 11:00 of September 20th the comfort indices are in category IV and thus really severe conditions with high level of PPD. It can be underlined that occupants have selected the analyzed set-point with the belief that they would be in comfortable conditions instead the normative approach suggests that the thermal sensation is near the cold. This indicates that the set-point should be higher and this would mean lower energy consumptions.

Furthermore, for all other available data, the distributions of calculated PMV and PPD are proposed, by considering different insulation levels for both diurnal and nocturnal hours. Figs. 13 and 14 show that the comfort zone is achievable for the higher percentage of values in the diurnal hours, if in the winter calculation the clothing resistance is assumed 1.0 clo and in the summer 0.7 clo. About the winter behavior, with 1.0 clo, the average PMV is −0.3. When the resistance is lower, the PPD increases with an average value higher of 30 % in case of 0.6 clo and 15 % with 0.8 clo. For the summertime, according to both standards, by reducing the clothing resistance from 0.7 clo to 0.5 clo (most common value), worse comfort conditions are observed with the PPD frequently higher than 10 %. As expected, from the analysis of T_{op}, the management strategy selected by the occupant could bring indoor condition classified as "not-comfortable" when the clothing resistance is lower than 0.7 clo.

Considering the nighttime period, the Category II is always achievable with 1.0 clo and 0.7 clo as clothing resistance during the winter and summer (Fig. 15). However, it must be taken into account that the heat pump is usually turned off, since the general indication of building managers is to have the heating/cooling services activated for not more than 10 h per day (Fig. 16). Thus, it can be also concluded that the building has good inertial properties, since during the winter the stored gains are utilized during the night to maintain the indoor conditions meanwhile in the summer the overheating problem is prevent.

More in general, the results underline that the evaluation of thermal environment strictly depends by all variables used in the calculation of the indicators and the occupant interviews are always needed. Thus, a sensitivity analysis is always advisable when the input parameters, as the clothing resistance, are not directly detected during the post-retrofit analysis. The results are in agree with the conclusions of some other works but for office buildings as [57] where the authors underlined that clothing insulation and metabolic rate can cause relevant errors.

4.2.2. *Indoor air quality analysis*

Fig. 17 shows the distribution of CO_2 concentrations usually lower than 430 ppm. The continuous adoption of mechanical ventilation allows having comparable distribution, median and quartile values in all three periods. Considering the limits proposed in Table 2, it can be stated that the bedroom is always in category I; this evaluation is based on the calculation of the variation compared to an average value of the outdoor concentration. The outdoor values were not monitored for the case study, but the analysis of historical concentrations proposed by Dimitriouet al. [58] for the same region has been considered. They have found an average daily value during the summer of 410 ppm, for the winter of 430 ppm and for the other seasons of 420 ppm.

The mechanical ventilation system, therefore, is able to guarantee a good ventilation rate. In particular, as suggested by UNI EN 16798 standard, the observed values correspond to the equilibrium concentration when the air flow rate is slightly higher than 7 l/s per person and the CO_2 is 13.6 l/h per person (bedrooms).

In the monitoring before the refurbishment, the concentrations of CO_2 have demonstrated highest values in all seasons (see Table 5). Indeed, the difference in the average value is usually higher than 50 ppm meanwhile, mainly during the winter, the maximum recorded values have important difference that underline the importance of the selected efficiency measures.

Regarding the exposure of the bedroom to the contaminants, Fig. 18 shows the distribution of TVOC concentration. In general, the building is configured as a very low-pulled building for 84 % of the hours both in the intermediate and summer seasons. Considering also the median and maximum values of the pre-retrofit period, there was a significant

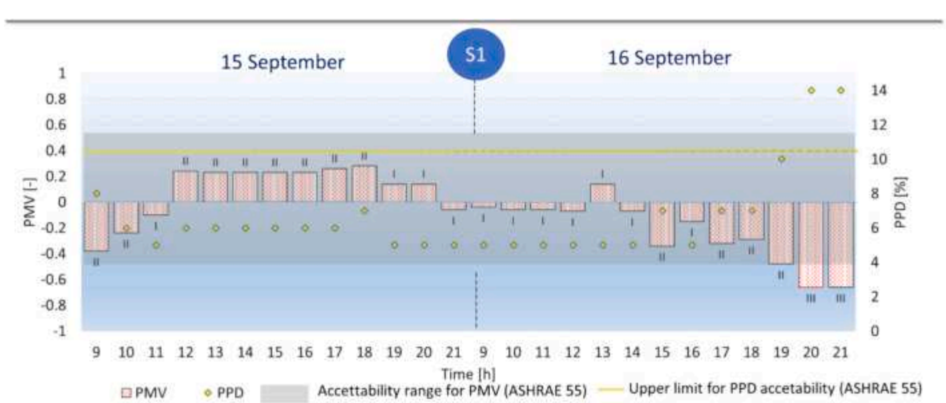

Fig. 10. PMV & PPD evaluation according to UNI EN 16798 and ASHRAE 55 – SUB-PERIOD 1.

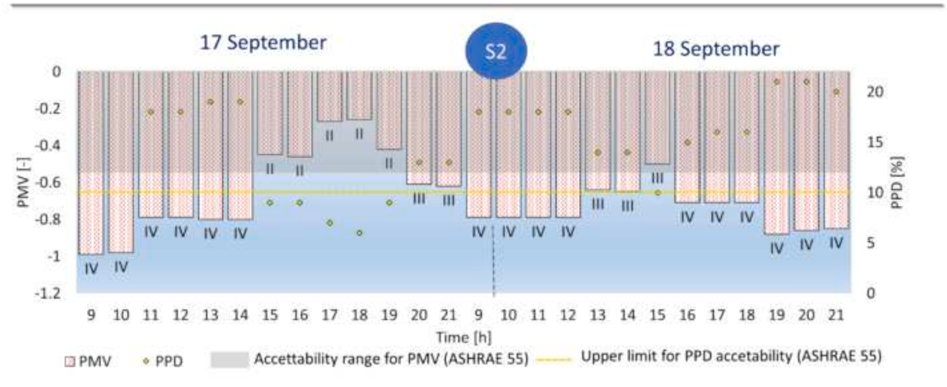

Fig. 11. PMV & PPD evaluation according UNI EN 16798 and ASHRAE 55 – SUB-PERIOD 2.

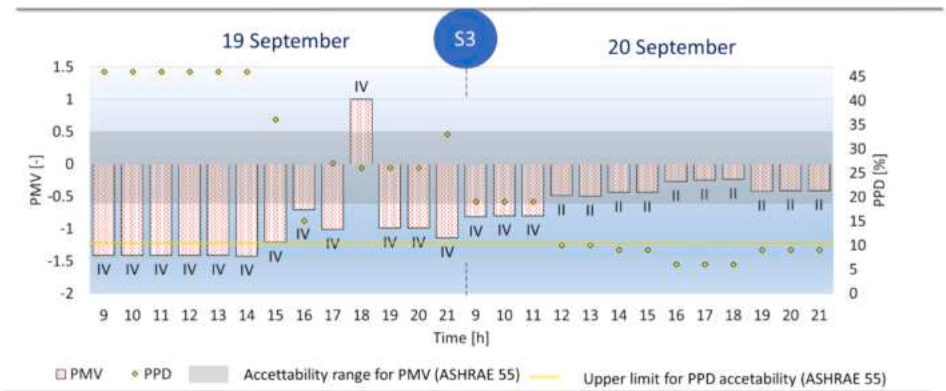

Fig. 12. PMV & PPD evaluation according UNI EN 16798 and ASHRAE 55 – SUB-PERIOD 3.

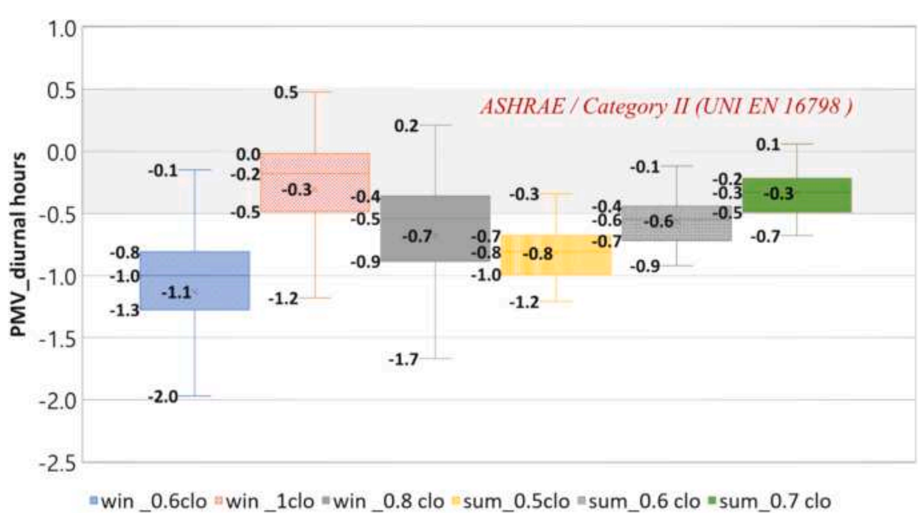

Fig. 13. Diurnal calculation of PMV according UNI EN 16798 and ASHRAE 55.

decrement of TVOC that assures to be always classified as a low polluted building since the concentration is consistently lower than 1000 μg/m^3.

Some problems are relived during the winter; in this case 26 % of values are lower than 300 μg/m^3 and 76 % lower than 1000 μg/m^3 thus, the building would be mainly classified as low polluting one. The extreme values are lower than in pre-retrofitted building (Table 5) and it allows concluding that the designed system improve globally the building indoor quality. However, some other analyses are under-evaluation for understanding if higher flow rate is necessary during the winter or if the measured values can be influenced by not-surveyed modification in the HP management. This seems confirmed from the detailed analysis developed for the first days of monitoring. Indeed, in the early morning of September 15th, when the heat pump is still not active, the TVOC concentration is varied between 989 μg/m^{3}and 1034 μg/m^3, then the daily average value has become 385 μg/m^3.

Furthermore, it can be concluded that the installed plant brings considerable benefits in terms of respiratory comfort for the occupants. This is also confirmed in terms of particulate matters, PM10 and PM2.5

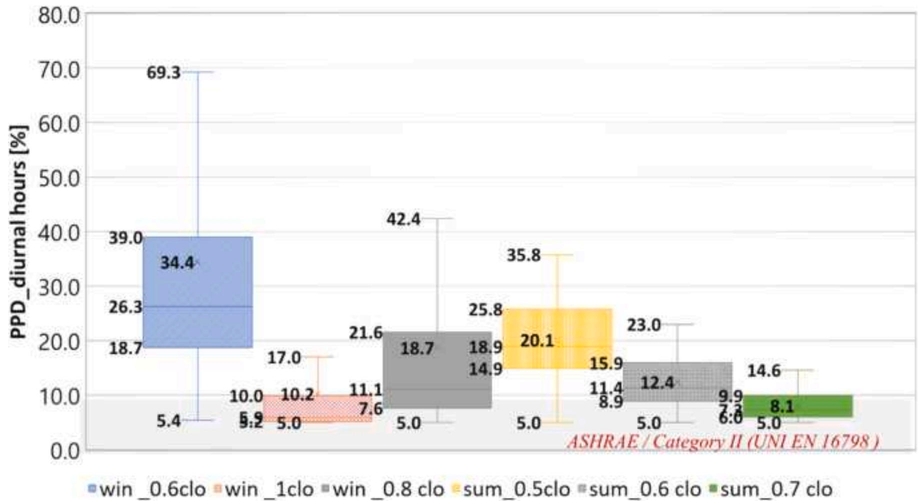

Fig. 14. Diurnal calculation of PPD according UNI EN 16798 and ASHRAE 55.

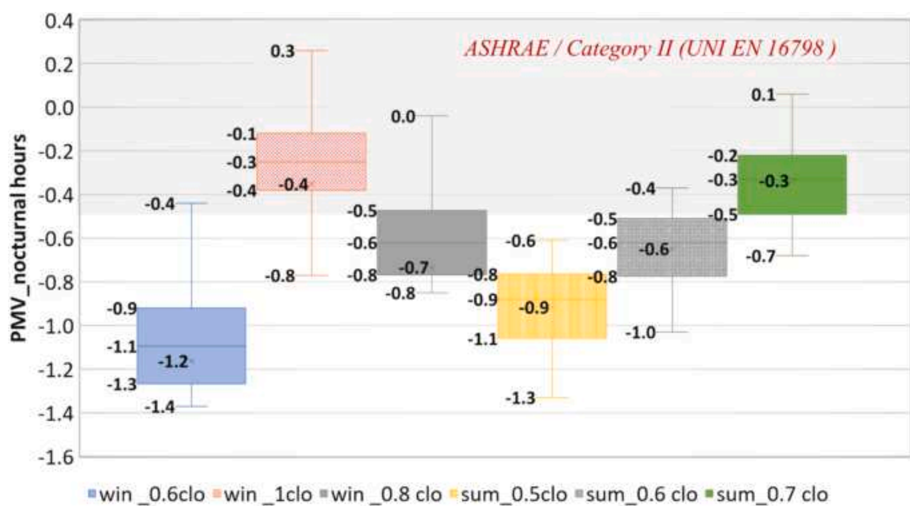

Fig. 15. Nocturnal calculation of PMV according UNI EN 16798 and ASHRAE 55.

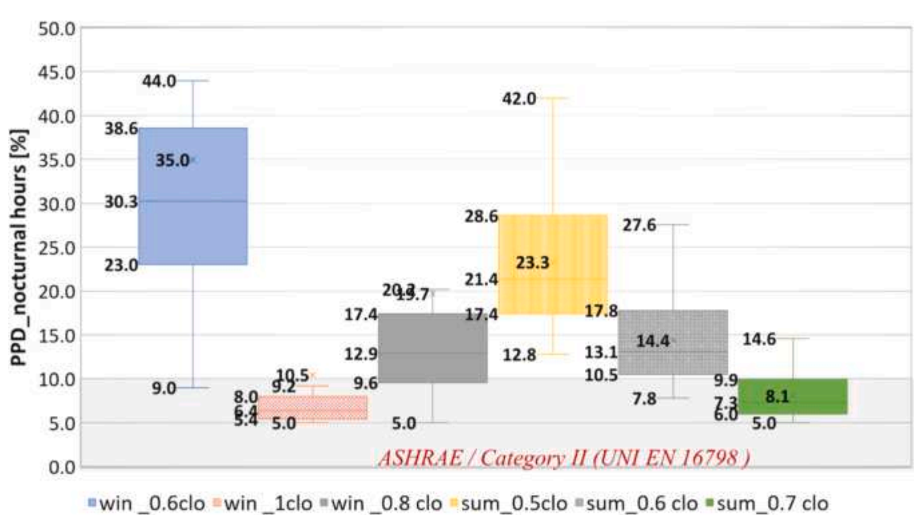

Fig. 16. Nocturnal calculation of PPD according UNI EN 16798 and ASHRAE 55.

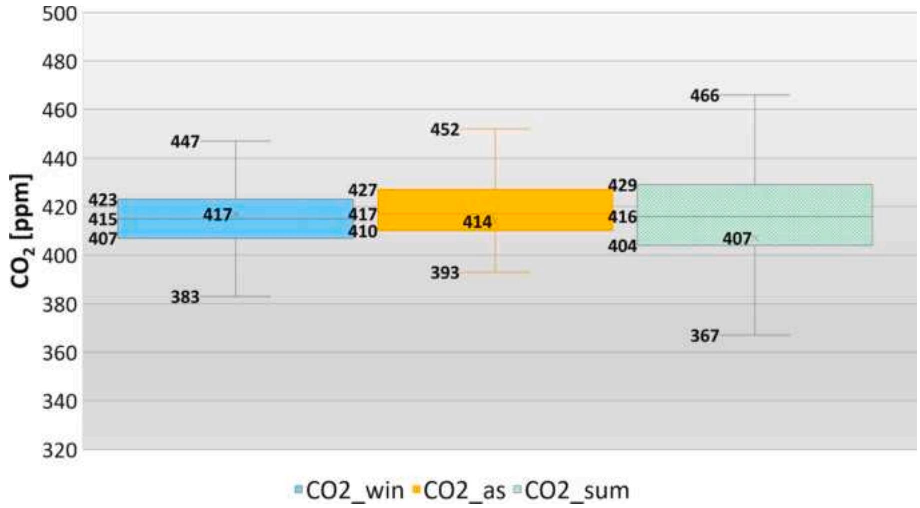

Fig. 17. Distribution of measured CO_2 concentration.

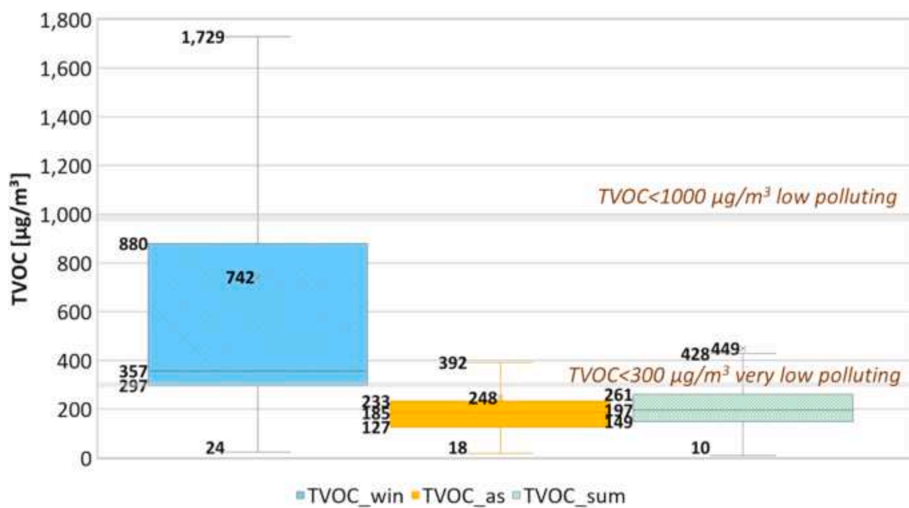

Fig. 18. TVOC concentration assessment.

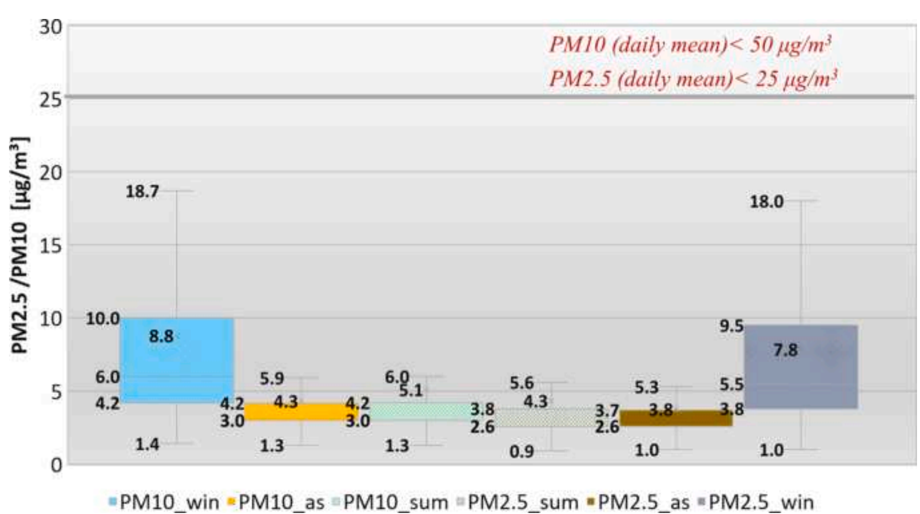

Fig. 19. Particulate matter concentrations (PM10 & PM2.5).

Table 6
Results of lighting measurements.

Day	Time (h)	Lighting (lux)
21/09/2022	8:00	80
21/09/2022	9:00	85
21/09/2022	10:00	120
22/09/2022	13:00	580
22/09/2022	14:00	740
22/09/2022	15:00	810
23/09/2022	17:00	1070
23/09/2022	18:00	1100
23/09/2022	19:00	1010

(Fig. 19) for which there are no data of the pre-retrofitted building. For both indicators the thresholds proposed by air quality standards are never reached.

4.2.2.1. Visual comfort analysis. The results of the measurements relating to the lighting level are reported in Table 6; in this case the monitoring campaign was conducted only in the last days of the project. However, more analyses will be proposed in further researches focused on the visual task. When the outdoor conditions are not favorable (cloudy sky), the minimum lighting level is not verified (21st September) also due to exposure of the room that receives direct radiation in the late afternoon. Instead in the following two days, the artificial lighting always guaranteed average values above 500 lux. In particular, in the afternoon of September 22nd, without the shading system and with clear sky, a minimum value of 580 lux at and a maximum value of 810 lux have been recorded.

In the evening of September23rd, the mean recorded level is on average above the considered target.

4.3. Qualitative evaluation through questionnaires

A general observation from the results of survey is the relatively high level of satisfaction for both groups about the thermal comfort since the average vote of 4.83 was found for Administrators/Engineers and 4.60 for User/Occupants. The highest satisfaction rate according to Users/Occupants is the positive impact on the social life of the campus meanwhile for Administrators/Engineers the highest satisfaction is observed for the sustainability aspects. In addition, the most important sustainable aspect is the installation of the new cooling system (4.70 for User/Occupants and 4.80 for Administrators/Engineers) that improves the occupants' well-being during the hot Greek summer.

More focused analysis will be developed in further studies with also a new survey also focused on the description of most common user's behavior description.

5. Conclusions

The paper introduces and applies a new method to verify the quality of the indoor environment after a deep refurbishment that modified the global insulation level, the façade structure adding volumes and the glazed surfaces as well as the HVAC configuration. The suggested approach is based both on qualitative analysis as the preliminary investigation on building envelope insulation level and the questionnaires for all the involved stakeholders and quantitative measures by means of readily monitored variables length to thermal, respiratory, and visual comfort. Also sensitivity investigations are proposed in the method for improving the readability of results obtained with the application of standardized indicators for the selection of indoor quality category.

The proposed method was applied to verify the performance of the student dormitory belongs to the National and Kapodistrian University of Athens undergone to architectural and environmental restructuration in the frame of the European Project Project Pro-GET-OnE (N°723747) ended at September 2022.

Some general conclusions were found by the case study: the refurbishment of the building envelope and the adoption of attached extra-room space applied in loggia allow stabilizing the indoor conditions improving the global quality both in term of thermo-hygrometric comfort and air-quality. In the intermediate seasons, the maximization of solar gains utilization and the adopted insulation levels guarantee an average temperature most comply near 24 °C; for the winter months the building can be classified for 80 % of time in category II according to UNI EN 16798 with an average temperature of about 20 °C. The summer period is the most critical but not for the overheating phenomenon rather for the selected set-point freely chosen by the occupants. Indeed, both daily and global analysis indicate that the operative temperature is usually near 23 °C and thus, the category II is achieved for around 60 % of the monitored period. This suggests the importance to do other analysis focused on the summer season about the effect of occupant behavior on the energy consumption and thermal-comfort indices. Indeed, severe set-points could bring to not good classification of the indoor environment according to the levels proposed by the traditional standards. On the other hand, it must to be taken into account that the occupants could decide to set low values for balance the outdoor overheating and thus the management strategy can be selected according to their preference. This is confirmed by the results of occupant's interviews that have indicated high satisfaction in term of thermal comfort. The occupant's well-being within a building is a key parameter for a successful renovation process beyond the possible classification.

The second general remarkable aspect is the weight that individual parameters, as the clothing insulation, have on the building classification. This was also demonstrated in the scientific literature for other kind of uses. More in detail, the proposed sensitivity analysis demonstrated that also a variation of 0.1 clo can modify the percentage of hours in discomfort range. For instance, in summer, with set-point of 25 °C, passing from 0.6 to 0.5 clo the percentage of hours with PMV and PPD inside category III and IV, according to the UNI EN 16798, increases from 8 % to 15 % and from 0 % to 12 %, respectively. With the same set-point temperature, if a clothing insulation of 0.7 clo is adopted, the percentage of hours is null. Similarly, during the winter, both considering nocturnal and diurnal hours, the median value of dissatisfied people passes from around 6 % with 1.0 clo to 12 % with 0.8 clo.

The analysis of indoor air quality has highlighted the key role of mechanical ventilation, when the building has high airtightness, to achieve the classification of very low-polluting building since monitored CO_2 is commonly lower than 430 ppm. Furthermore, the ventilation assures both in summer and intermediate seasons an average daily value of TVOC below 300 μg/m^3 as a very low-polluting building.

However, not all findings were positive. Indeed, the long-term monitoring has indicated that the management strategy and some subjective variables can change the classification of indoor quality mainly as regard the thermal comfort in summer and the air quality during the winter. For these reasons a sensitivity analysis is suggested in the ex-post analysis.

CRediT authorship contribution statement

A. Gigante: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Papadaki:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Mazzoli:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **V. Ntouros:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **R.F. De Masi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.-N. Assimakopoulos:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Annarita Ferrante:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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