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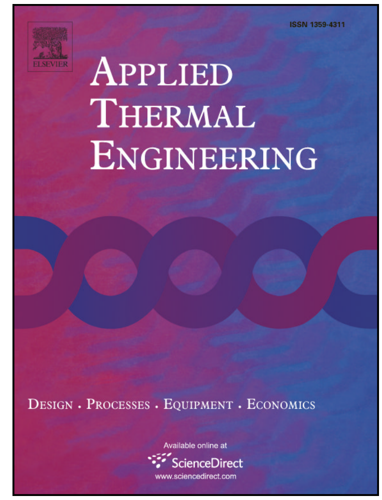

Research Paper

Improvement of thermal comfort and energy efficiency in historical and monumental buildings by means of localized heating based on non-invasive electric radiant panels

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Improvement of thermal comfort and energy efficiency in historical and monumental buildings by means of localized heating based on non-invasive electric radiant panels

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ABSTRACT

Energy efficiency and thermal comfort in historic buildings are very often hampered by preservation needs. This issue is particularly relevant for historical and monumental buildings, which currently represent a large part of the historic buildings stock in Europe. For such protected buildings most of the available retrofitting solutions are not feasible and alternatives have to be investigated to guarantee their usability potential. The purpose of this study is therefore to present a methodology to evaluate the potential of electric radiant panels as retrofitting solutions for historical and monumental buildings, focusing on thermal comfort and energy saving potential when compared with conventional fossil-fuel-based heating systems. In fact, the non-invasiveness and flexibility of electrical panels make them one of the few feasible solutions for protected buildings.

An original methodology is developed to evaluate the performance of such localized heating systems; the methodology is based on a dynamic simulation model, calibrated with

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temperature measurements, which takes into account the geometry and technical characteristics of electrical radiant panels and allows different control strategies to be compared. The methodology is applied to a relevant Italian historical building. The results show that the panels, despite their well-known low-exergy efficiency, may become a viable and attractive solution for historical buildings without undermining their preservation requirements. Apart from significantly increasing thermal comfort, electric radiant panels may also allow annual heating energy savings up to 70% for the selected building.

Keywords: Electrical heating; Personalized conditioning systems; Comfort; Historic buildings; Building energy simulation.

1. Introduction

Nowadays buildings account for about 40% of the total energy consumption of the European Union (EU) and the share is continuously expanding [1]. Around a quarter of the existing buildings stock in Europe was built prior to the middle of the last century [2]. The problem is particularly relevant in countries like Italy, where about 20% of the existing buildings were built before 1919 [3] and about 40% of world artistic heritage can be found according to UNESCO estimates [4]. Many of European historic buildings, often valued for their cultural, architectural and historical significance, not only reflect the unique character and identity of European cities but include essential infrastructures for housing or public services. A significant number of historical and monumental buildings are poorly insulated and use conventional inefficient fossil-fuel-based energy systems, typically associated with high energy costs and CO_2 emissions. Despite of the relatively high energy need, indoor thermal comfort is often scarce. The most common reasons for discomfort are related with insufficient local thermal control, poor insulation, large vertical temperature gradients and inadequate mean radiant and operative temperatures perceived by the occupants.

Although exceptions are available at national level to exclude historic buildings from the application of energy efficiency requirements [5], energy related issues should be addressed to guarantee the usability potential of such buildings. Moreover, the application of environmental certification and sustainability rating systems to heritage buildings is becoming increasingly important and should be further developed in the upcoming years [6].

Many energy retrofitting solutions are not compatible with historic buildings, especially for listed or protected ones. In such cases, “non-invasive” but often less performing solutions have to be chosen, sometimes associated with a higher investment cost than Best Available Technologies [7]. While this issue seems to only marginally interest discontinuously occupied historical buildings, it is particularly significant for historical buildings that are used for residential, working and educational purposes, which actually represent the greatest part of the historic buildings stock [7]. Most of historic buildings are currently institutional buildings [8], like schools, universities, town halls and administrative services. To properly design and operate such buildings, a number of parameters which characterize most of historic institutional buildings, such as large thermal inertia and intermittent and variable usage, should be taken into account [9]–[12].

Another common problem related with historic buildings is the difficulty to fully assess and reliably model the energy performance of many different building types across Europe and to assess the effect of energy measures or more sustainable solutions. Different studies can be found in the literature on procedures to assess and model the energy performance of historic buildings [13]-[15]. In most cases a need for dynamic simulation of the building energy performance is identified, which allows to properly take into account both the large thermal inertia of such buildings and the effects of intermittent usage and activation of HVAC systems.

Conventional heating systems of historic buildings are often hydronic systems with radiators. These systems have high installation and energy costs [16] and often do not guarantee thermal comfort because the buildings are characterized by intermittent usage, large heat loss through the building fabric, significant rooms height, single glazed windows, draughts and infiltration losses. In addition, especially for damp climates, a certain level of ventilation is necessary to disperse indoor moisture [17]. In order to enhance thermal comfort and energy savings without undermining cultural, architectural and historical significance, only few solutions can be applied. The installation of heat pumps is often not feasible due to the aesthetic impact of external units and the difficult fixing of the internal unit on refined walls. They might be installed in correspondence of inner courts, but the well-known issue of cold air stratification in the courts may significantly decrease their heating efficiency. The installation of the coolant tubes would also be a critical issue for heritage-protected walls. With regards to thermal insulation, an internal installation is relatively easy and reversible, even though it is not always applicable in historic buildings (e.g. on frescoed walls) [18]. Among possible retrofitting solutions, personalized heating systems can be an efficient and cost-effective option, especially for buildings characterized by intermittent usage. Such systems aim to create a microclimate around a person, optimizing energy consumption while providing thermal comfort [19]. The benefit of such systems when compared with neutral ambient control systems is the necessity to condition only the heated island around each workstation and the potential enhanced comfort due to the higher control on the operative temperature perceived by the occupant. Recently Zhang et. al. [20] provided examples of comfort levels associated with energy-saving ambient control, in which personalized cooling systems allow the comfort to remain equivalent to, and in some cases better than, that of neutral ambient control. The results showed that a considerably wide range of indoor temperatures can be experienced when using these systems. In contrast to studies on personalized cooling, only a few studies deal with personalized heating as an energy saving solution [21]. Most of the investigated systems are feet or hand warmers, which normally might extend the range of conventional heating systems but cannot be substituted to them. The studies of Foda and Sirén [22] and Vissers [23] both report heating energy savings of 17% for personalized heating systems when the conventional heating set point was decreased and the energy need of the personalized heating system was taken into account. The system presented in the study of Zhang et al. [24] included personalized feet and hands warmers, reporting annual heating energy savings in the range of 30% to 60%, when the conventional heating range was extended from 21.5–24 °C to 18–30 °C. In addition, the authors reported that there was no discomfort noted when the occupants left their workstations for short breaks.

Only a few studies on heated islands are focused on historic buildings and no studies are found in literature on the performance of electric radiant panels as a retrofitting solution for historic buildings. Bertolin et. al. [25] studied the effect of local heating with IR thermal radiation for the pews of two churches in a very cold climate, evaluating best conditions of thermal comfort compatible with artworks conservation.

One of the novelties brought by this study is the assessment of the energy performance of electric radiant panel systems for historical and monumental buildings by using a calculation methodology based on dynamic simulation, calibrated with air temperature measurements and an operative-temperature-based control strategy. The methodology allows to evaluate the case when the radiant panel systems completely substitute rather than integrate the existing heating system.

The building chosen as case study is a relevant historic institutional building in northern Italy, which is used for military and academic purposes, and the analysis is carried out at office level. This paper focuses on the improvement of the thermal comfort of the building achievable by the adopted heating systems and on their energy saving potential. The analysis of the proposed retrofitting solutions is carried out also in terms of economy and environmental influence.

2. Description of the case study

In this study, the Ducal Palace of Modena has been selected as reference building. This building, home of the Este family for two centuries, is one of the most important Sixteenth Century princely palaces in the world (see Fig. 1). The Palace currently houses the Italian Military Academy, the Military Museum and a library [26].

Figure 1. External view of the Ducal Palace of Modena.

The building has four floors for a total gross heated volume of about 425’000 m^3. The supporting structure is built with rubble masonry and marble is used for the façades decoration. The windows are all wooden-framed and single glazed. The wooden roof supporting structure is mostly covered by tiles. Thickness and thermal transmittance of the envelope components are shown in Tab. 1. In absence of in situ measurements, the thermo-physical properties of the envelope components were assessed by means of on-site inspections and National Technical Standards [27] indicating the material properties of existing Italian buildings. The wall described refers to the selected offices. Different thickness can be found in other areas of the building. Anyway, the walls, roofs and floors presented in Tab. 1 are representative of most of the building variety in terms of component layers. Thermal bridges are not considered since their effect is generally negligible in not-insulated masonry buildings.

Table 1. Characteristics of the building envelope components.

Component type	s [m]	U [W/(m^{2}K)]
Wall	1.04	1.2
Window	-	3.8
Roof	0.55	1.0
Floor	0.52	1.8

The existing heating system is a conventional hydronic one, composed by three gas boilers and radiators often positioned under the windows. The hydronic circuit is largely made by poorly insulated steel tubes for an approximate length of 3000 m, leading to a significantly low distribution efficiency, typical of such large historic buildings. Moreover, the control system is only based on the external temperature, without any room air temperature compensation. The duration of the heating season is established from October 15th to April 15th, according to the Italian law [28].

A thermal discomfort is generally perceived by occupants, especially during winter time, probably caused by lack of insulation and by air stratification in the rooms, which can reach the height of 7-9 m. The thermal discomfort can also be caused by the windows, which cannot guarantee an adequate level of air tightness because of their very large size and the aging of the wooden frame. The situation is particularly critical for the office area, located in the south-west wing of the building as it is characterized by more continuous occupation than other areas. In this study, some representative offices from this area are thus chosen as case study and modelled in detail. The main geometrical characteristics of the selected offices are summarized in Tab. 2, where "opaque vertical surfaces" refers to both external and internal walls. Office 1 and Office 2 are located on the second floor, Office 3 and Office 4 on the third floor (see Fig. 2). Office 2 and Office 4 currently host four workstations each while Office 1 and Office 3 have only one workstation.

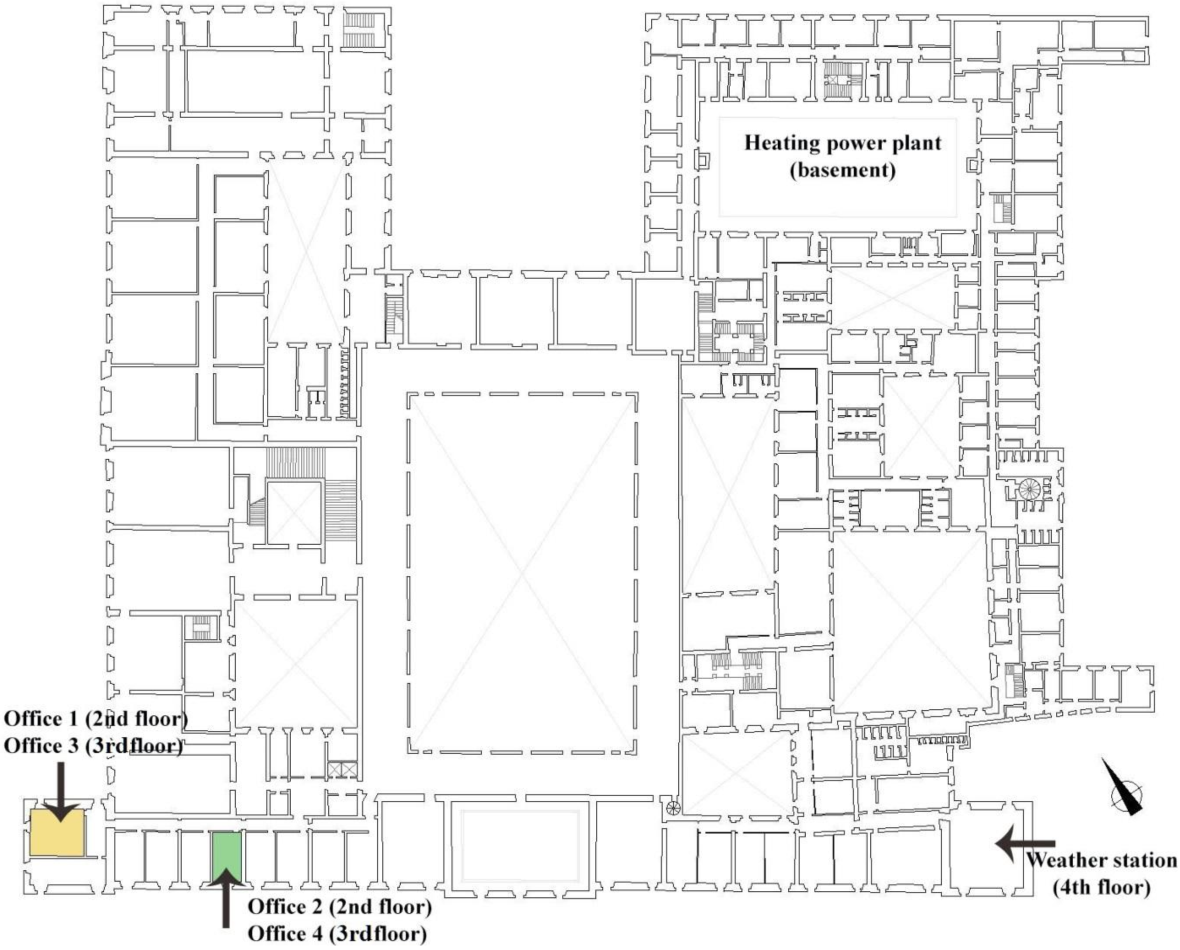


Figure 2. Plan of the building.

Table 2. Main geometrical characteristics of the selected offices.

Geometrical characteristics	Office 1-3	Office 2-4
Floor surface [m^2]	56	32
Opaque vertical surfaces [m^2]	169	138
Transparent surfaces [m^2]	10.6	5.3
Gross volume [m^3]	336	192

3. Methodological approach

3.1 Energy modelling and calibration

The simulations have been carried out using TRNSYS 17 dynamic thermal modeling software [29]. Each of the selected offices is modeled as a different thermal zone (see Fig. 3).

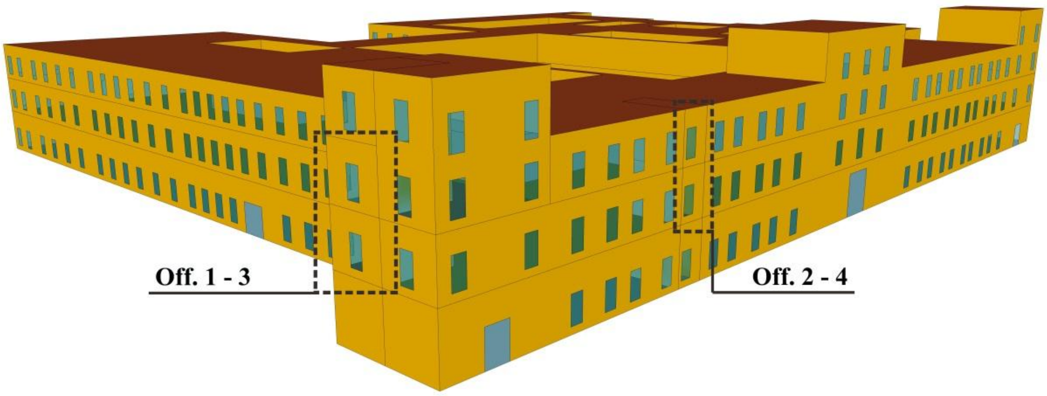


Figure 3. Building Simulation Model.

Table 3. Internal gains of the selected offices.

Internal Gains	Office 1-3	Office 2-4
Number of workstations	1	4
Activity of occupants	Seated, light work, typing	Seated, light work, typing
Equipment (for all workstations)	230 W PC with colour monitor	920 W PC with colour monitor
Lights	100 W/m^2 lamps	100 W/m^2 lamps

Internal gains, such as lighting, equipment and occupants (see Tab. 3), are defined according to the conventional opening hours of the selected offices, i.e. in working days from 8:00 to 19:00 and confirmed with data gathered during audits. The surfaces of the selected offices that are adjacent to other offices are assumed to have negligible heat transfer. This is justified by the fact that all offices located in the south-west wing are heated with the same time schedule and they have similar occupancy profile, interior loads, constructions and dimensions. In addition, interior walls (brick walls with a thickness of 46 cm) increase the thermal mass of the building and reduce the thermal interaction between adjacent rooms. Air infiltration losses have been estimated with the calculation method of ISO 13789 [30]. In particular, for offices 1 and 3 the infiltration air change rate has been assumed 0.6 h^{-1}, while 0.5 h^{-1} has been defined for offices 2 and 4. Such average values are used due to the unavailability of more detailed information. Difference among offices is due to the different exposition.

The simulations were conducted over 3 consecutive heating seasons (from 2012/2013 to 2014/2015). The meteorological data used in the simulations were collected by the University of Modena and Reggio Emilia weather station, which is located in the selected building (see Fig. 2). The hourly weather data include horizontal global radiation, dry bulb temperature, wind speed and relative humidity [31].

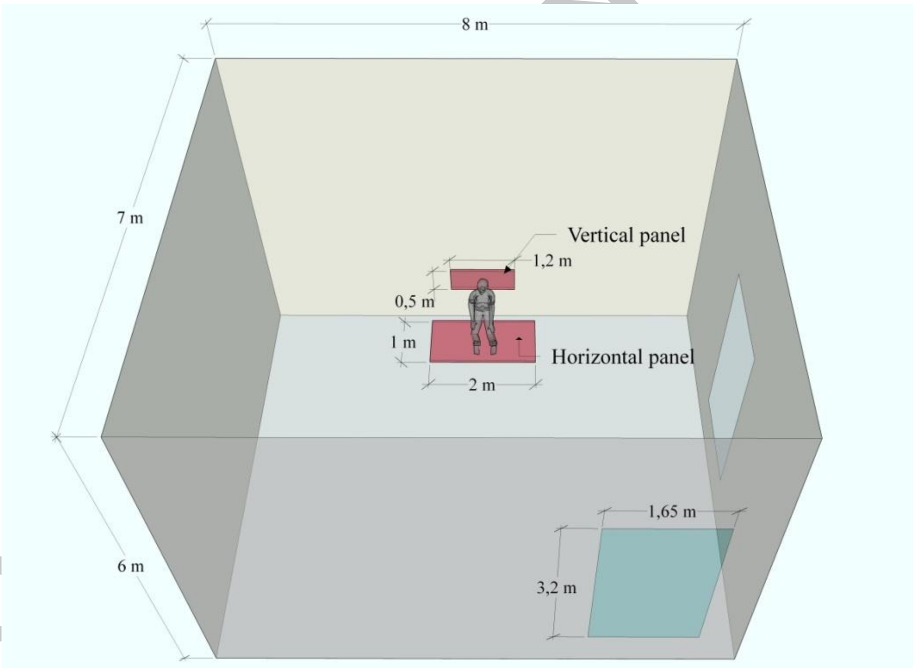
Hourly indoor air temperature measurements were used to calibrate the dynamic simulation model of the building. The normalized mean bias error (NMBE) and the coefficient of variance of the root mean square error (CV(RMSE)) were used for the analysis, according to ASHRAE guideline 14 [32]. In cases when relative humidity data are available, a more sophisticated calibration can include also humidity assessment. The indoor air temperature was measured by data loggers with embedded temperature sensors, with accuracy of ±0.5°C, positioned at 1.5 m height in correspondence of the workstations. The indoor air temperature measurements were collected in 5 min intervals and averaged to hourly data. The overall monitoring period covers two weeks in October 2014 and two weeks in January 2015. An unoccupied period of one week was used in order to better capture the thermal dynamics of the envelope.

Once the model of the building envelope was calibrated, internal gains and actual heating system were defined for each thermal zone by considering the characteristics of actual systems and schedules. The radiators have been simulated in TRNSYS with a specific component (Type 1231). The hydronic system losses have been estimated with the methods defined in UNI/TS 11300-2 [33], which specifies the national application procedure of different international technical standards, such as EN 15316 [34].

3.2 Model for the analyzed retrofitting solutions

The energy performance of the selected offices with the current hydronic system is compared with the energy performance of different retrofitting solutions using electric radiant panels. As retrofitting solutions, each workstation was supposed to be heated by a three-panel system. This is composed by two (0.6x0.6 m^2) vertical panels positioned behind the seated person and one (1.0x2.0 m^2) floor panel below the workstation (see Fig. 4). The panel below the workstation is separated from the floor by a 3 cm insulation layer. The sizes are selected based on commercially available products [35].

The maximum temperature of the vertical panels was set to 40 °C, 50 °C or 60 °C, while for the floor panels the maximum temperature was set to 29 °C, in compliance with ISO 7730:2006 [36]. A summary of the parameters varied in the simulations is given in Tab. 4.



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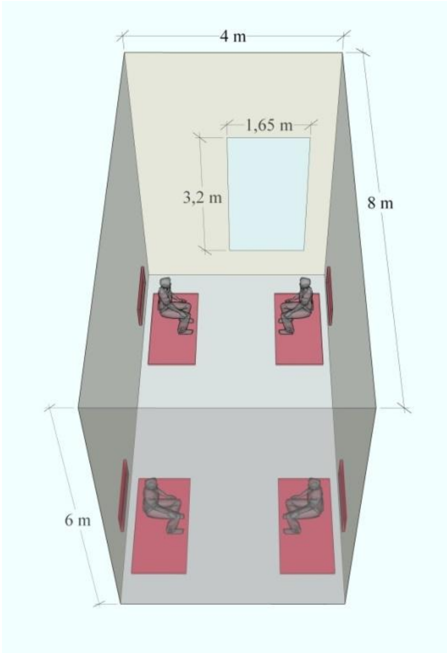
b. 

Figure 4. Geometries of the selected offices and of the electric radiant panels:
a. Offices 1-3; b. Offices 2-4.

Table 4. Parameters varied in the simulation cases.

Simulation Case	Max vertical panel temperature ($T_{pan,v,max}$)	Max horizontal panel temperature ($T_{pan,h,max}$)
Electric 40/29	40°C	29°C
Electric 50/29	50°C	29°C
Electric 60/29	60°C	29°C

The operation of radiant panels and comfort levels of the analyzed workstations have been assessed by dynamic simulation.

It is assumed that the three-panel system is automatically turned off when there is no occupant. The required surface temperature of the three-panel system was calculated for each time-step by fixing a target operative temperature $T_{op,des}$ of 20°C, given the relatively high clothing level of occupants, normally wearing military uniform, and the overall physical characteristics of such historic buildings. In addition, this is the same operative temperature required in Italy for residential and office buildings during the heating season.

For occupants engaged in near sedentary physical activity, not in direct sunlight and not exposed to air velocities greater than 0.2 m/s, the operative temperature may be approximated with acceptable accuracy as the average of the mean radiant and ambient temperatures [37]:

$$T_{op} \cong \frac{T_{mr} + T_a}{2} \tag{1}$$

Consequently, the target mean radiant temperature, taking into account the surface temperatures of ceiling, floor, walls, windows, and electric radiant panels, can be obtained as per Eq. (2):

$$T_{mr,des} \cong 2 \cdot T_{op,des} - T_a \tag{2}$$

A surface-to-surface radiation model was used to account for the radiation exchange between the surfaces in the room. The energy exchange between two surfaces depends on their size, separation distance, and orientation. These parameters are accounted by a "view factor" geometric function F_{P-Ai}. The view factors from the panels to the occupants have been calculated for each workstation based on the equations defined in Dunkle [38]. In particular, 0.090 and 0.049 has been used as view factor for respectively the horizontal panel ($F_{P-pan,h}$), and the vertical panels ($F_{P-pan,v}$) of each workstation.

As a result, the target mean radiant temperature is given for each workstation by Eq. (3):

$$T_{mr,des} = \left(1 - F_{P-pan.v} - F_{P-pan.h}\right) \cdot T_{mr,w} + F_{P-pan.v} \cdot T_{pan,v,des} + F_{P-pan.h} \cdot T_{pan,h,des} \tag{3}$$

Therefore the target temperature of the electric radiant panels can be obtained from Eq. (3). In this regard, a control strategy has to be applied to define the vertical and floor panels simultaneous activities. In this study, linear relations are investigated, as per Eq. (4):

$$T_{pan,h,des} = \min\left(29°C, T_{op,des} + k \cdot \left(T_{pan,v,des} - T_{op,des}\right)\right) \quad (4)$$

where k is a proportionality coefficient to define the level of simultaneous activity. In the investigated cases it has been found by preliminary analysis that k=1 (i.e. $T_{pan,h,des}$ = $T_{pan,v,des}$) provides the lowest energy consumption and higher comfort levels and it was applied to all simulation cases. This means that $T_{pan,h,des}$ is set equal to $T_{pan,v,des}$ until $T_{pan,v,des}$ reaches 29°C. For $T_{pan,v,des}$ values exceeding 29°C, $T_{pan,h,des}$ is set equal to the upper allowed value, which is 29°C.

Solving Eqs. (2), (3) and (4) with respect to $T_{pan,v,des}$ results in Eq. (5):

$$T_{pan,v,des} = \frac{2 \cdot T_{op,des} - T_a - \left(1 - F_{P-pan.v} - F_{P-pan.h}\right) \cdot T_{mr,w}}{F_{P-pan.v} + F_{P-pan.h}} \quad (5)$$

Therefore $T_{pan,v,des}$ and $T_{pan,h,des}$ can be calculated for each time step as a function of $T_{op,des}$, T_a, $T_{mr,w}$, $F_{P-pan,h}$ and $F_{P-pan,v}$. When $T_{pan,v,des}$ is higher than $T_{pan,v,max}$ (see Tab. 3), $T_{pan,v,des}$ is set equal to $T_{pan,v,max}$.

The heating systems performance is subsequently evaluated for the selected offices. The analysis is based on primary energy consumption, operating costs and carbon dioxide emissions. The heating primary energy consumption is calculated by using the following equation:

$$E_{tot} = E_n \cdot f_n + E_e \cdot f_e \quad (6)$$

where E_n represents the consumption of natural gas (in kWh), E_e represents the electrical energy consumption (in kWh), f_n and f_e stand for the primary energy conversion coefficients for respectively the natural gas and the electrical energy. These coefficients are defined as the ratio of total input of the energy resources (hydro, coal, oil and natural gas) and the final produced energy. The value of f_n for Italy is 1.05, while the value of f_e for the electricity mix is 2.42 (given by the sum of 1.95 for the non-renewable component $f_{e,nren}$ and 0.47 for the renewable component $f_{e,ren}$) [39].

The total operating costs to run the systems are calculated by using the following equation:

$$C_{tot} = E_n \cdot c_n + E_e \cdot c_e \tag{7}$$

where c_n stands for the specific cost of consumption of natural gas (in €/ kWh), and c_e stands for the specific cost of consumption of electrical energy (in €/ kWh). The operating costs data are determined by using mean values for such type of buildings, respectively equal to 0.085 €/ kWh for natural gas and 0.20 €/ kWh for electricity.

The total yearly CO_2 emission during system operation has been calculated, using the Italian conversion coefficients for natural gas (56.989 t CO_2eq /TJ) and electricity (326.78 g CO_2eq /kWh) [40].

3.3 Comfort analysis

Thermal comfort levels have been defined basing on predicted mean vote (PMV), operative temperature, and local thermal discomfort, according to ASHRAE 55 [37] and ISO 7730 [41]. The PMV index is based on the heat balance of the human body and is calculated through six variables. The values used in the calculations are described in Tab. 5.

Table 5. Variable values used to determine the PMV index.

Variable to determine the PMV index	Value
Metabolic rate [W/m^2]	70
Clothing insulation [clo]	1
Indoor air temperature [°C]	Hourly values from simulation results
Indoor mean radiant temperature[°C]	

Indoor air relative humidity [%]	
Indoor air velocity[m/s]	0.1

Besides describing the sensation of the body as a whole, percentages of dissatisfied are used to indicate also a local thermal discomfort, which happens when a particular part of the body is perceived as too cool or too hot. In the particular case presented by this study, the proposed radiant heating system can affect thermal comfort for the effect of radiant asymmetry, even if in general people are more sensitive to asymmetric radiation caused by a warm ceiling than that caused by hot vertical surfaces.

Horizontal and vertical radiant temperature asymmetry is defined as the difference between the temperatures seen by a vertical or horizontal planar element respectively, positioned at 0.6 m above the floor and representing the barycenter of the human body [37]. In Tab. 6 the view factors between the horizontal and vertical planes and the surfaces of the thermal zones are summarized; their calculation has been performed externally by the authors. Every surface has been divided in four parts depending on the position of the occupant of the considered workstation. Radiant temperature asymmetry has been calculated according to [42], using the mean radiant surface temperatures obtained by simulations and the above mentioned view factors. Following a conservative approach, for Office 2 and Office 4 only the most uncomfortable workstations have been considered, positioned nearby the external wall, that is the coolest surface, which could produce the highest radiant temperature asymmetry.

Table 6. View factors between surfaces and planar elements.

Offices 1-3				Offices 2-4			
Surface - description and position			F_{P-Ai}	Surface - description and position			F_{P-Ai}
Floor	Front	Left	0.0995	Floor	Front	Left	0.0978
	Front	Right	0.0995		Front	Right	0.0867
	Rear	Left	0.0430		Rear	Left	0.0434
	Rear	Right	0.0430		Rear	Right	0.0410

Ceiling	Front	Left	0.0378	Ceiling	Front	Left	0.0331
	Front	Right	0.0378		Front	Right	0.0151
	Rear	Left	0.0044		Rear	Left	0.0055
	Rear	Right	0.0044		Rear	Right	0.0025
East wall	Upper	Left	0.0272	East wall	Upper	Left	0.0645
	Upper	Right	0.0272		Upper	Right	0.0342
	Lower	Left	0.0038		Lower	Left	0.0117
	Lower	Right	0.0038		Lower	Right	0.0067
North wall	Upper	Front	0.0600	North wall	Upper	Front	0.0757
	Upper	Rear	0.0079		Upper	Rear	0.0183
	Lower	Front	0.0101		Lower	Front	0.0201
	Lower	Rear	0.0015		Lower	Rear	0.0056
South wall	Upper	Front	0.0600	South wall	Upper	Front	0.0274
	Upper	Rear	0.0079		Upper	Rear	0.0044
	Lower	Front	0.0101		Lower	Front	0.0040
	Lower	Rear	0.0015		Lower	Rear	0.0007
West wall	Upper	Left	0.1046	West wall	Upper	Left	0.1070
	Upper	Right	0.1046		Upper	Right	0.0961
	Lower	Left	0.0609		Lower	Left	0.0613
	Lower	Right	0.0609		Lower	Right	0.0588
Vertical panel			0.0323	Vertical panel			0.0323
Horizontal panel			0.0462	Horizontal panel			0.0462
Total			1.0000	Total			1.0000

Target comfort categories are described by standards ISO 15251:2008 [43], and ISO 7730:2005 defines their corresponding PMV and PPD acceptable ranges (see Tab. 7).

Table 7. Target comfort categories and their boundaries.

Comfort category		Thermal state of the body as a whole PPD %	PMV %	DR %	Local discomfort PD% Vertical air temp. Difference	Caused by Warm or cool floor	Radiant asymmetry
A	High level of expectation	< 6	− 0.2 < PMV < + 0.2	< 15	< 3	< 10	< 5
B	Medium level of expectation	< 10	− 0.5 < PMV < + 0.5	< 20	< 5	< 10	< 5
C	Moderate level of expectation	< 15	− 0.7 < PMV < + 0.7	< 25	< 10	< 15	< 10

Comfort category “B” has been chosen to evaluate the global and local discomfort for all the different simulation cases. In particular, the analysis of thermal discomfort is focused on the evaluation of the radiant asymmetry. Moreover, it was evaluated whether the relative humidity and operative temperature values generated by the simulated cases are within the comfort zone, as defined by ASHRAE 55.

The proposed methodology is summarized in Fig. 5.

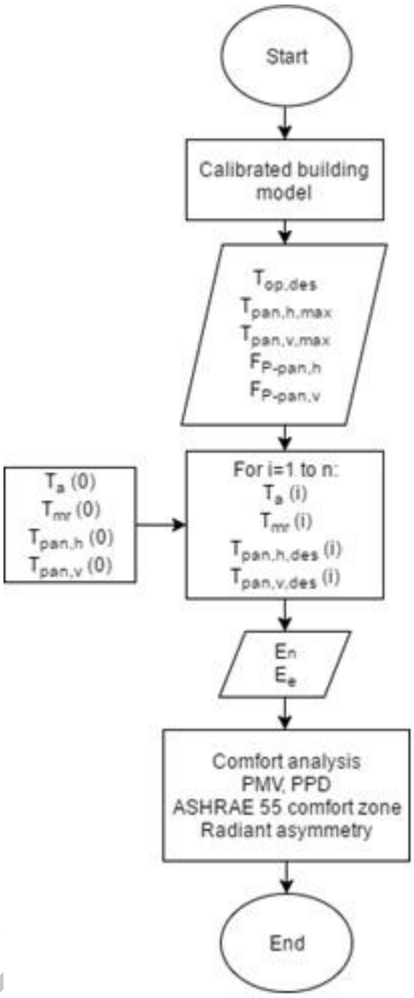


Figure 5. Flow chart of the methodology.

4. Results and discussion

The calibration of the dynamic simulation model has been obtained using hourly indoor air temperature measurements. Statistical analysis were performed to evaluate the discrepancies between simulated and current building energy performance. The normalized mean bias error (NMBE) and the coefficient of variance of the root mean square error (CV(RMSE)) were used for the analysis. Respectively, the NMBE and the CV(RMSE) of the hourly indoor air temperature were 2% and 5%. The results show that the selected indexes are in agreement with the tolerance range [32] and the model has been considered representative of the actual energy performance of the selected offices.

Fig. 6 presents the monthly means, averages of all the daily maximum and minimum temperatures, for each month of the monitored heating seasons. The monthly mean temperature ranged between 3.7°C (December 2012) and 16.7°C (October 2014).

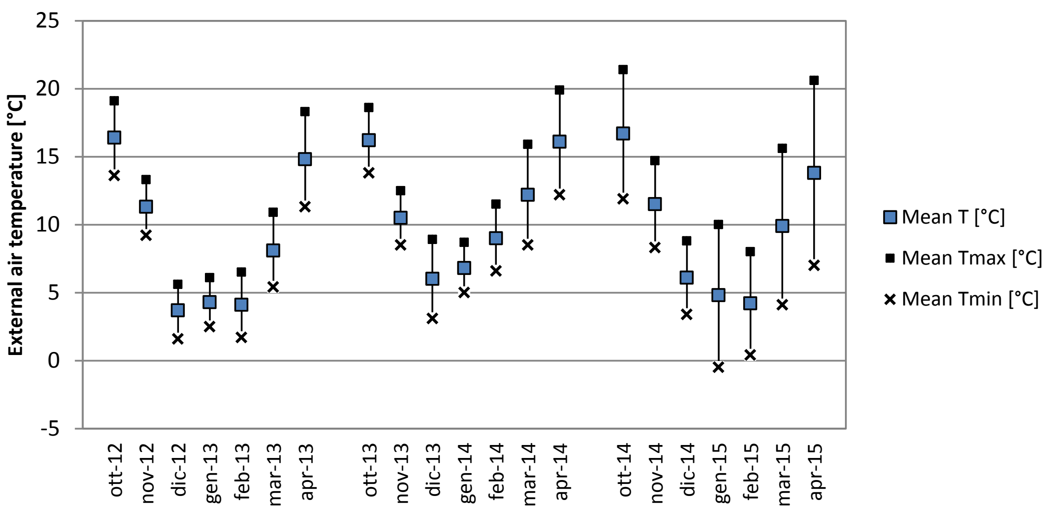


Figure 6. Monthly mean temperatures from the weather station for the selected heating seasons.

Results are obtained in terms of energy consumption, CO_2 emissions, operating costs and comfort levels. Fig. 7 represents primary energy consumption of the current hydronic system and the simulation cases with maximum temperature of vertical panels of 40°C and 60°C. Panels with 50°C temperature yields intermediate values. The results show that the use of electric panels allows to achieve average reductions in primary energy consumption ranging from 10% to 75%. The lowest reduction is obtained for Office 4, which is situated in the most unfavorable position among the selected ones, due to the contiguity with the roof. On the contrary, the highest energy savings are obtained by Office 1 and Office 3, where only one workstation is present.

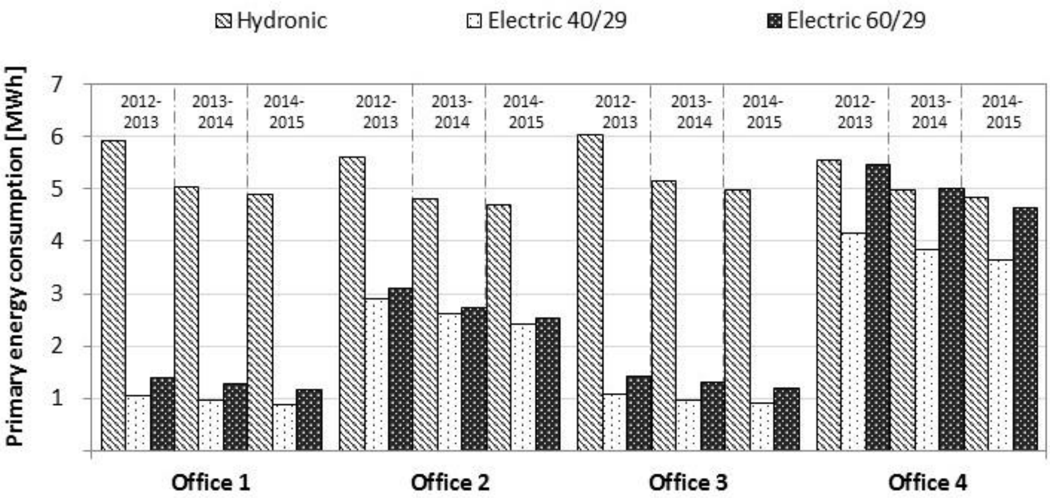


Figure 7. Heating primary energy consumption of the selected offices: comparison between the existing system and two retrofitting solutions (max. temperature for vertical panels of 40°C and 60°C).

The overall achievable savings in heating energy consumption implies avoided CO_2 equivalent emissions in the range of 25% to 80% of the electric system compared to the current hydronic one.

Reduction of operating costs due to the retrofitting solutions are shown for some representative cases (see Fig. 8). The graphs show a significant reduction of specific operating costs for Office 1 and Office 3 (i.e. on average about 80%) when the retrofitting solutions are considered. The lowest costs savings are achieved for Office 4, which has the highest occupation density and it is adjacent to the external roof. The comparison of the results for the different heating seasons shows that the retrofitting solutions provide the highest operating costs reduction for heating seasons with lower monthly maximum ambient temperatures (i.e. higher daily degree days). Operating costs also increase when higher maximum temperatures are considered for the vertical panels. In particular, the costs raise from 40°C to 60°C is about 30% for all the selected offices except Office 2, for which the increase is about 5 %. This result shows that for Office 2 the hours when the panel would reach 60°C are significantly lower compared to the other selected offices.

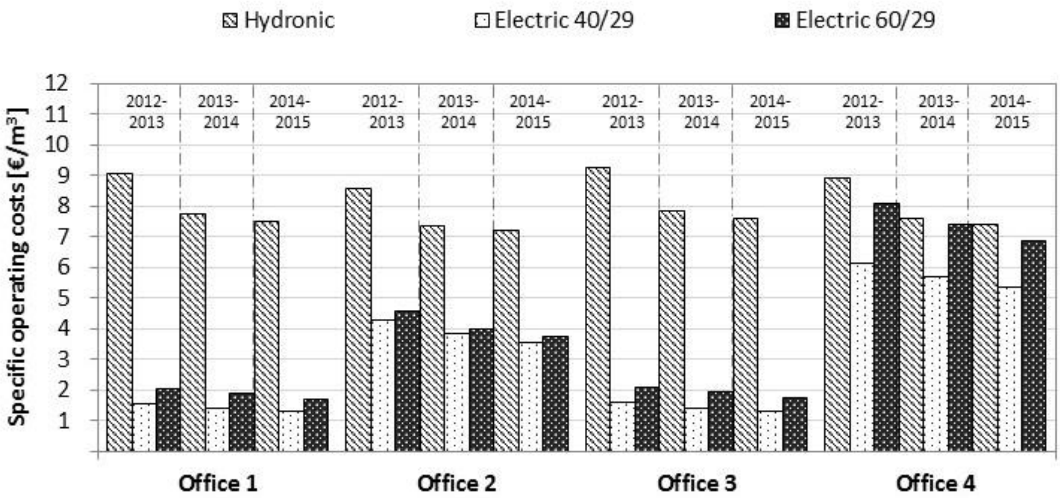


Figure 8. Specific operating costs: comparison between the existing system and two retrofitting solutions (max. temperature for vertical panels of 40°C and 60°C).

Local thermal comfort for the selected retrofitting measures has been compared with the existing condition. The results, obtained in terms of PMV index, are summarized in Fig. 9. The graph shows the significant comfort improvement achieved by the retrofitting solutions. In addition, it has been found that setting higher maximum temperatures does not yield to significant improvements in the comfort level.

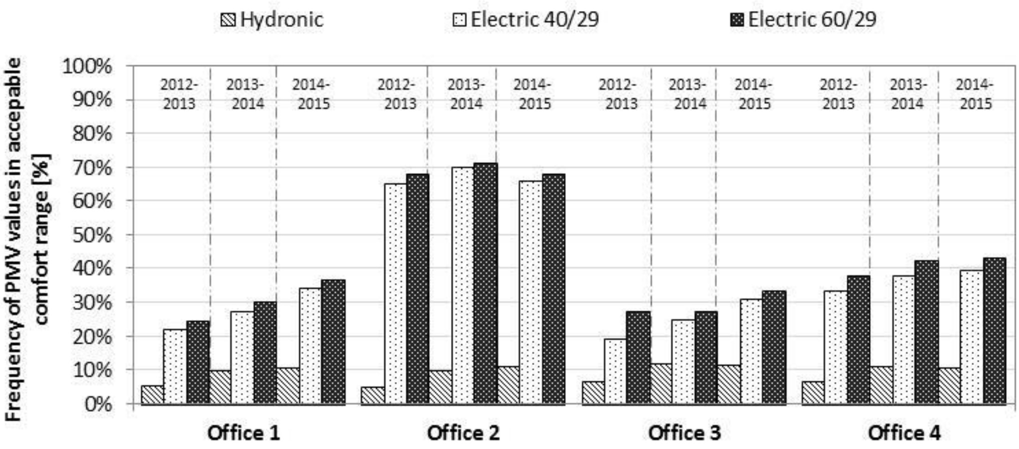


Figure 9. Frequency of PMV values in an acceptable comfort range (-0,5 < PMV < 0,5) for the selected offices. Retrofitting solutions and the current hydronic system.

Fig.10 and Fig. 11 show the frequencies of PMV index in different acceptable ranges. Compliance with the ASHRAE 55 comfort zone is shown as well. The graphs have been produced considering only the values corresponding to the occupancy period of the offices.

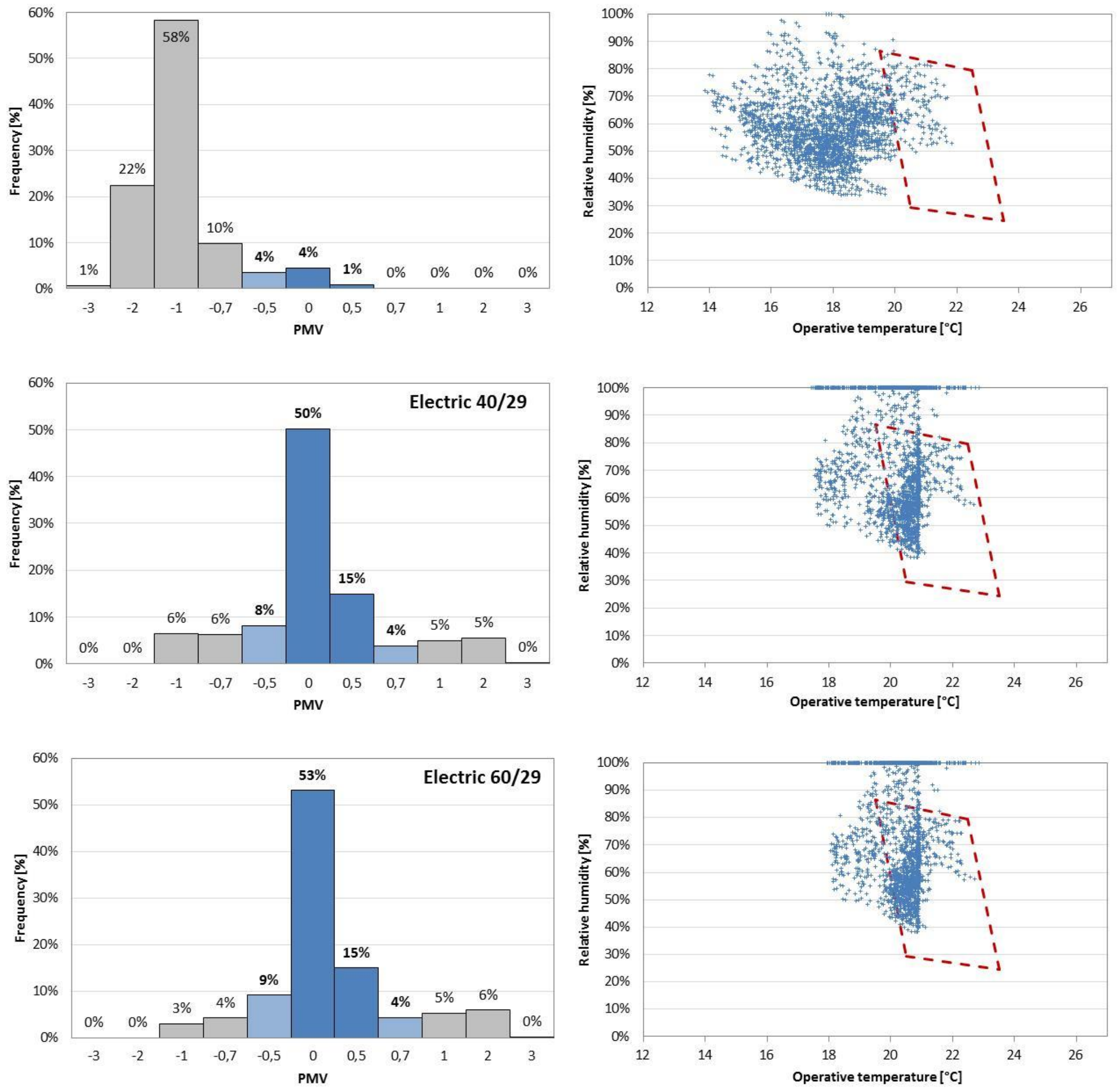


Figure 10. Left: frequencies of PMV values in acceptable comfort range (blue columns: -0.5 < PMV < 0.5, light blue column: -0.7 < PMV < 0.7) – Right: operative temperature and humidity in ASHRAE 55 comfort zone (Office 2, heating season 2012-13).

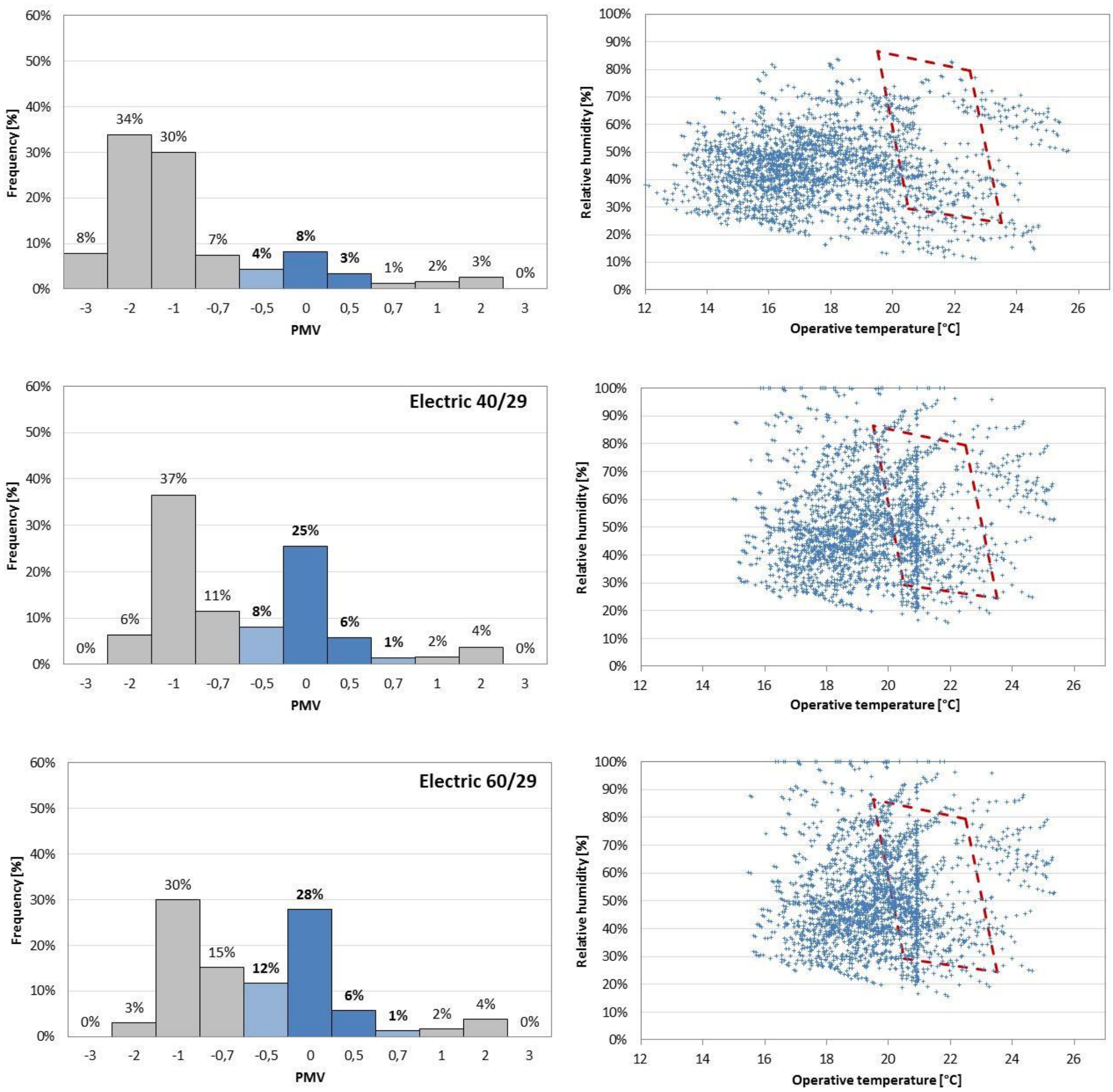


Figure 11. Left: frequencies of PMV values in acceptable comfort range (blue columns: -0.5 < PMV < 0.5, light blue column: -0.7 < PMV < 0.7) – Right: operative temperature and humidity in ASHRAE 55 comfort zone (Office 3, heating season 2014-15).

Among the selected offices, the best results in terms of comfort are achieved for Office 2: specifically, even for the coldest heating season, PMV frequency for a medium level of expectation varies from a 5% with the existing system to a 68% with the electric radiant panels. Office 3 presents the lowest comfort improvement: for example, during 2014-15 heating season PMV frequency in an acceptable comfort range varies from 11% to 34%. Despite the low comfort improvement of Office 3 compared to other analyzed offices, the retrofitting solutions allow to mitigate the thermal discomfort identified with the current hydronic system.

For this particular case study, concealed condensation issues are unlikely to happen due to the high infiltration air change rate and the absence of significant water sources, as often occurs in historical and monumental buildings. A high relative humidity may be occasionally reached in some rooms due to the lower air temperature, as shown in Fig. 10, with the consequent risk of vapor condensation on the internal surface of outer walls. However, the risk can be minimized by installing simple and inexpensive electric dehumidifier in the involved rooms, to be automatically activated when relative humidity rises above a given limit.

The improvements in operating costs are summarized in Fig. 12 for each of the selected offices. Office 1 and Office 3 present the highest cost reductions while Office 4 presents the lowest reduction of operating costs, although significant comfort improvements are guarantee for all heating seasons.

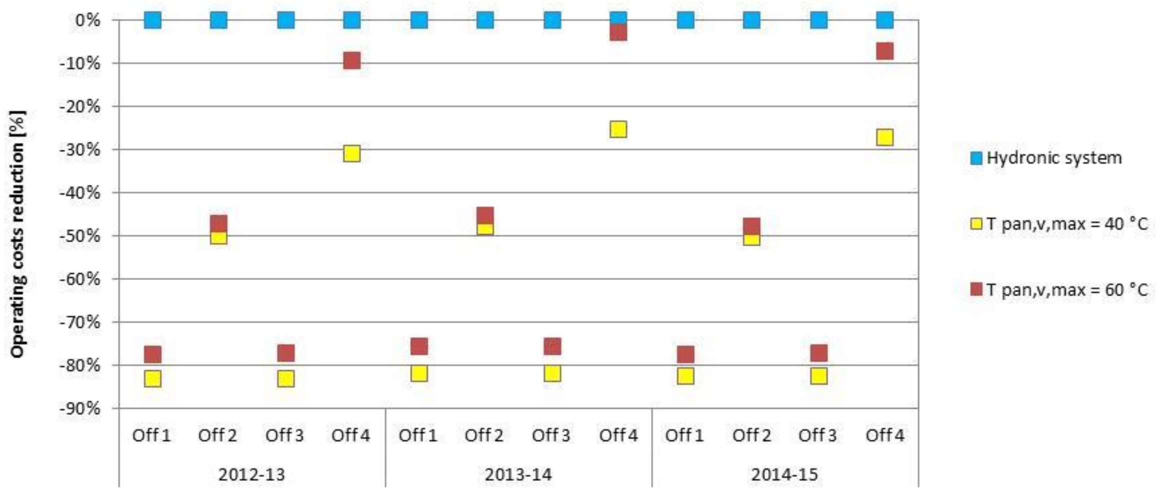
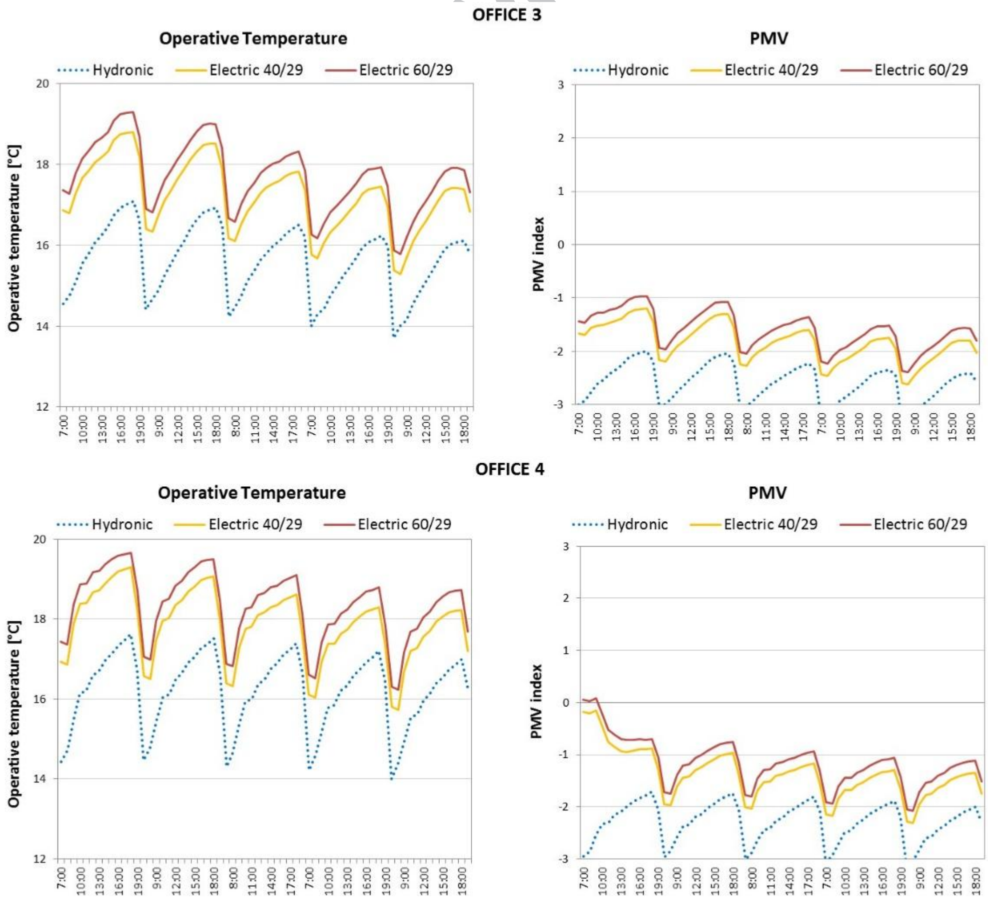
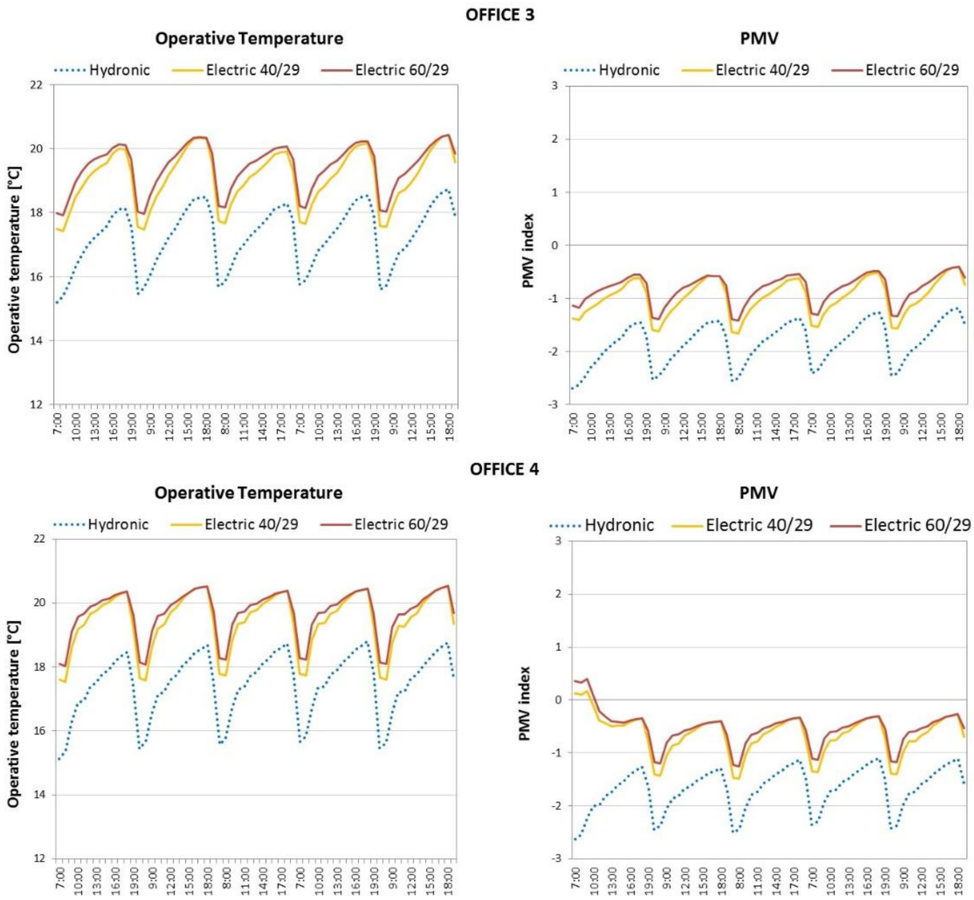


Figure 12. Comparison between the electric panels system and the current hydronic system in terms of reduction of operating costs.

A detailed analysis of comfort conditions is shown in Fig. 13 for the coldest week of the analyzed heating seasons and during one representative week of March 2014. These weeks are selected as representative of the worst and average situation for the comfort of occupants During the coldest week the operative temperature ranges between 14°C and 18°C in offices 3 and 4 t and the PMV index values vary between -1.5 and -3. General sensation of slight cold or cold is perceived. The graphs show that with the radiant panels system, the operative temperature values range respectively between 15°C and 19°C or 16°C and 20°C. PMV index values also become significantly closer to the comfort range compared to the current situation. A similar improvement is experienced during the week of March, with operative temperatures ranging from 17°C to 21°C when the radiant panels are considered.



a.



b.

Figure 13. Operative temperature and PMV index for Office 3 and Office 4: a. during one cold week of December 2012; b. during one week of March 2014.

Finally, the obtained results show that the selected retrofitting solutions yield to an acceptable radiant asymmetry effect: the limiting values of PD caused by radiant asymmetry has never been exceeded (PD indices lower than 1.5%).

5. Conclusions

This paper presents a methodology to evaluate the potential use of electric radiant panels for historic institutional buildings with existing inefficient fossil-fuel-based central heating systems. The proposed evaluation methodology is based on dynamic simulation and temperature monitoring.

The effects of the electric panels on operative temperature and energy need are calculated by the dynamic model itself, in which an algorithm has been implemented in order to better describe the effect of the electric heating system on the microclimatic variables of the analyzed thermal zones. The control strategy of the panels is based on the operative temperature to optimize the efficiency of the system and evaluate the maximum benefit of such personalized heating solution. Hourly indoor air temperature measurements were used to calibrate the dynamic simulation model of the building. In cases when relative humidity data are available, a more sophisticated calibration can include also humidity assessment.

The energy performance of the retrofit system is evaluated for some representative offices of the Ducal Palace of Modena. The results of the case study shows the ability of the electric radiant panels to maintain an acceptable thermal comfort – in the workstation rather than in the whole room – as well as the energy saving potential compared with conventional hydronic systems. Since the Palace has several zones with very different schedules of usage, the expected benefits brought by radiant panels applied to other rooms should be even greater.

The analysis shows the significant improvement of thermal comfort yielded by the electric radiant panels. Furthermore, it is found that the adopted heating system also leads to a significant energy saving potential. In particular, the results show that energy savings are particularly significant for offices with only one workstation. It has to be noted that the comfort analysis performed in this study is based on the widely used heat balance theory. More recent approaches based on adaptive comfort concept, which consist in exploring the effects of humans' adaptation to thermal conditions, can be applied in future work.

The radiant panels system represents a remarkable solution during all the analyzed heating seasons, even in the coolest days, and best results in terms of energy savings are obtained for heating seasons with higher values of daily degree days. Besides, the comfort analysis related to the whole heating seasons show that setting higher the panels maximum temperatures does not improve significantly the comfort level. The selected building is characterized by significantly low distribution efficiency, typical of such large historic buildings, which often cannot be directly improved due to the building preservation needs. When higher distribution efficiency is considered, lower reductions in primary energy consumption can be experienced.

It can be concluded that electric radiant panels may allow significant CO_2 emissions reductions in historical and monumental buildings, even if electricity has the highest carbon emissions per delivered kWh among common heating fuels. Moreover, aspects like the reduction of local pollution, the increase of efficiency within the electric grid distribution network and the increase in renewables sources within the energy mix, have also to be included in the retrofitting decision-making process. In this regard, the current average efficiency of the Italian grid has been considered here, equal to 41.3% (*i.e.* the inverse of the primary energy conversion coefficient for electricity f_e=2.42), but almost 20% of the grid energy (*i.e.* $f_{e,ren}/f_e$) already comes from renewable sources, and new generation plants with efficiency in excess of 60% are expected to enter into service.

The proposed methodology can be applied to other climatic contexts to evaluate the convenience of the proposed retrofitting solutions. Future work will assess additional energy saving potential of the combined effect with other energy retrofitting strategies, suitable to heritage buildings. The methodology will also be applied to some historic buildings of the University of Modena and Reggio Emilia in the framework of the University Energy Plan.

Nomenclature

Variables

C	cost	[€]
c	specific cost	[€/kWh]
E	energy need	[kWh]
F	view factor	[-]
f	primary energy conversion coefficients	[-]
k	proportionality coefficient	[-]
s	thickness	[m]
T	temperature	[°C]
U	thermal transmittance	[W/(m^2 K)]

Subscripts

a	air
des	design
e	electricity
h	horizontal
max	maximum
mr	mean radiant
n	natural gas
nren	non-renewable
op	operative
P–pan	from person to panel
pan	electric panel
ren	renewable
tot	total
v	vertical
w	walls

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HIGHLIGHTS

- Energy retrofit solutions are presented for historical and monumental buildings.
- The efficiency of electric radiant heating systems on thermal comfort is analyzed.
- An operative temperature-based control is applied in a dynamic simulation model.
- Energy need is reduced while increasing thermal comfort by using electric radiant panels.
- A high comfort improvement is achieved in the analyzed offices even in the coolest days.