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Assessment of different HVAC configurations in a Conference Room with thermal stratification for improved microclimate conditions

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Abstract. The paper aims to investigate the microclimate conditions within a conference room, namely the chapel of Villa San Saverio presently housing the "Scuola Superiore" of the University of Catania, as a case study. Initial surveys of the chapel involved monitoring air temperature and relative humidity. Subsequently, numerical simulations utilizing a simplified computational fluid-dynamics (CFD) model, built with DesignBuilder software, were conducted and validated against measured values. Three scenarios were simulated, encompassing the existing state without thermal systems and two configurations incorporating both air-conditioning and ventilation. Results indicate that, for optimal comfort, a lightweight radiant floor heating system, coupled with a floor-level ventilation system for air renewal near occupants, proves superior to floor-level fan coils and high ventilation channels. This finding is further supported by a basic energy analysis comparing the two HVAC options. The analysis considers winter ventilation effectiveness, emitter water temperature, COP value of the heat pump, and electricity consumption of the various components. This comprehensive approach provides valuable insights for enhancing comfort and energy efficiency in enclosed spaces, offering practical applications for similar environments.

Key words. Microclimate, historic building, HVAC systems

1. Introduction

The issue of reducing the energy consumption of buildings is a pressing and timely concern. Buildings account for 36% of greenhouse gas (GHG) emissions and 40% of final energy consumption in Europe, with approximately 70% of this energy consumption linked to heating demand [1], [2], [3]. This has necessitated the development and evolution of various technologies related to thermal systems. These technologies, which include specific configurations tailored for both new constructions and the existing architectural heritage, aim to improve energy efficiency and reduce GHG emissions [4].
One particular challenge in the design of technical systems is addressing thermal stratification in tall buildings [5], [6], [7] and churches. The significant height typical of such places of worship [8] often leads to uneven temperature distribution, with warmer air rising to the top and cooler air settling at the bottom.
As a result, it is common for ecclesiastical buildings to lack thermal systems [9], [10], [11], [12], not only due to the issue of thermal stratification but also because the installation and operation of such systems can potentially cause damage to the valuable artworks housed within these buildings.
When planning to repurpose an environment with a large vertical development, which is common for heritage buildings, the choice of a technical solution for the thermal system can significantly impact operational energy consumption.
In these types of buildings, the use of convective systems can lead to unnecessary energy consumption, as the occupants typically only use the lower part of the building. This research, therefore, analyses different types of technical systems that can provide thermal comfort and effective ventilation for occupants. It demonstrates that it is possible to achieve satisfactory comfort conditions with specific technological systems in historic buildings with large volumes, thereby avoiding the unnecessary heating of air in the upper layer.
The case study selected for this analysis is the chapel of Villa San Saverio, the location of the "Scuola Superiore" of the University of Catania. Computational fluid-dynamics (CFD) simulations were carried out and validated against experimental measurements for comfort analysis purposes. The study presents a comparison between a configuration composed of fan coils and induction ventilation channels, and a radiant floor system.
To create and validate the virtual model of the building, the air temperature was monitored over four winter days in March 2022 during a pause in the ongoing renovation works. This monitoring allowed for a more accurate representation of the building's thermal behaviour, contributing to the development of more effective and energy-efficient thermal systems.

2. Materials and Methods

2.1. Case Study and monitoring approach

The case study building is settled within the historic Villa San Saverio, which currently serves as the prestigious location of the "Scuola Superiore" of Catania, Italy. This esteemed institution is a higher education centre of the

University of Catania, established in 1998 [13]. Villa San Saverio is an architectural gem, boasting a large internal courtyard and rich decorative elements that elevate its cultural significance (as depicted in Figure 1).

Fig. 1. General view of Villa San Saverio

Constructed in 1880, the villa initially served residential purposes for the first two decades of its existence. Its history is steeped in academia and spirituality, having been the location of the "Istituto Agrario Siciliano Valdisavoia", the "Collegio San Luigi di Birchircara di Malta", and the Jesuit Community [14].

In 2001, its path converged with the University of Catania, further enriching its historical narrative [15].

As for its architectural features. the net height at the keystone of the barrel vault soars to about 10.80 m. The floor, inclusive of the apse, spans a net area of about 125 m^2 and is oriented with the long side (approximately 18 m in length) facing North. The total net width measures about 7.50 m, and the radius of the apse extends to about 3.70 m. The north and south facades open to the outdoors, while the other two facades partially adjoin other parts of the building complex. The walls, with a thickness of 0.80 m, are constructed with irregular lava stones, adding to the rustic charm of the building. The roof, a vaulted (barrel type) structure, is crafted in pumice and plaster conglomerate, topped with a wooden gable roof and tile roof. The main entrance is an imposing external door with two solid wood panels measuring 2.00 m x 3.70 m. Additionally, there are two secondary entrances of 1.50 m x 2.95 m, strategically placed in the middle of the two longitudinal sides.

In the clerestory, above the cornice located at a height of 6.55 m, six windows allow natural light to filter into the chapel. Three of these windows are in the apse area, one is above the entrance door, and the remaining two are placed on the two longitudinal walls. The window on the south facade measures 2.30 m x 3.20 m, while the others measure 1.50 m x 1.80 m. To validate the model subsequently built on the dynamic energy simulation software DesignBuilder, a series of thermo-hygrometric measurements were carried out from 4^{th} to 7^{th} March 2022.

Despite the short period of measurement, the experimental activity yielded valuable insights, thanks to the careful selection of both the monitoring days and probes' position, following the approach outlined in [16]. Specifically, two types of instruments were used to measure the air temperature (their technical features are reported in Table 1 and 2): two Wöhler CDL 210 dataloggers were positioned respectively at 4 meters and 6 meters from the floor and a TESTO 435 heat flow meter equipped with a probe for measuring the air temperature was positioned at a height of 1 m from the floor.

Table 1. Technical features of Wöhler CDL 210 datalogger.

	Temperature	Relative humidity
Measuring range	-10 °C to +60 °C	5 % to 95 %
Resolution	0.1 °C	0.1 %
Accuracy	± 0.6 °C	± 3 % for 10% and 90%, ± 5 % otherwise

Table 2. Technical features of the TESTO 435 datalogger.

	Temperature
Measurement range	from -50°C to 100°C
Resolution	0.1 °C
Accuracy	± 0.2 °C when -25 °C < T < 74.9 °C ± 0.4 °when -50 °C < T < -25.1 °C ± 0.4 °C when 75 °C < T < 99.9 °C ± 0.5 % for all other values

This meticulous approach to data collection ensures the accuracy and reliability of the simulation model, contributing to the development of energy-efficient solutions for such historic buildings.

2.2. CFD Modeling

The 3D model (Fig.2) was realized using the DesignBuilder software, a powerful tool that not only facilitates the creation of 3D models but also enables the performance of Computational Fluid Dynamics (CFD) simulations.

DesignBuilder provides an intuitive modelling environment where users can construct the building model in three dimensions and assign a variety of thermal and physical attributes such as materials, thermal loads, and technical systems [17].

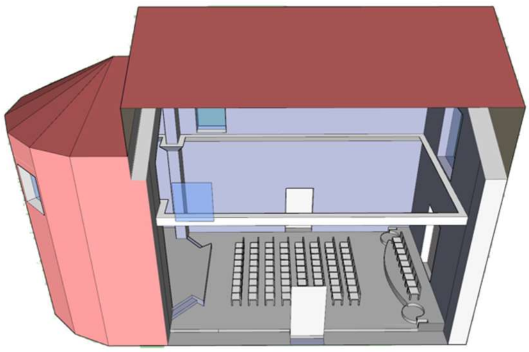

Fig. 2. DesignBuilder 3D Model – Current state (Case 0)

To conduct the necessary simulations, a simplified three-dimensional model was constructed.

Notable modifications include the rectification of the apse, approximation of the apsidal basin to planar pitches, omission of the triumphal arch, and disregard of the 17 cm height difference between the nave and the apse area. These simplifications were implemented with the primary objective of this analysis in mind: to understand the vertical distribution of air temperature, especially in the areas of the chapel frequented by the public.

Therefore, special attention was given to accurately modelling the vertical development of the building, ensuring that the highest point of the nave (approximately 10.80 m from the floor) was retained as measured in situ.

Following an in-depth survey conducted in situ, specific thermal characteristics were assigned to the opaque and transparent envelope components of the building.

The uninsulated external walls were assigned a thermal transmittance value (U-value) of 1.56 $W \cdot m^{-2} \cdot K^{-1}$. The pitched roof was assigned a U-value of 1.14 $W \cdot m^{-2} \cdot K^{-1}$. The ground floor was assigned a U-value of 1.46 $W \cdot m^{-2} \cdot K^{-1}$. The double-glazing of the openings was assigned a transmittance value of 2.70 $W \cdot m^{-2} \cdot K^{-1}$, while their wooden frame was assigned a thermal transmittance of 3.63 $W \cdot m^{-2} \cdot K^{-1}$. These values are crucial in understanding and optimizing the thermal performance of the building, and were gathered from other studies concerning the same geographical area and construction period [18], [19], [20].

2.3. Model Validation and Simulation Scenarios

To ensure the precision of the Computational Fluid Dynamics (CFD) model, simulations were executed by incorporating the recorded weather conditions from the local meteorological service from the 4th to the 7th of March 2022 [21].

The outcomes of these simulations in terms of air temperature distribution were then compared with the measured data at different heights (1, 4 and 6 metres), resulting in an average coefficient of determination (R^2) of 94%, an average Pearson's correlation coefficient (r) of 98%, an average Mean Absolute Error (MAE) of 0.37°C and an average Root Mean Square Error (RMSE) of 0.47°C, attesting to the accuracy and reliability of the CFD model in faithfully capturing the thermal dynamics of the building.

To assess the comfort conditions achievable with different thermal systems, three distinct scenarios were developed, and then compared in terms of air velocity distribution, air temperature distribution, and Predicted Mean Vote (PMV) distribution [22]:

1. The first scenario, referred to as "Case 0", represents the current state of the building without any thermal systems;
2. The second scenario (Fig.2), "Case 1", incorporates a technical system comprising floor-level fan coils for heating/cooling, supplemented by two perforated ventilation channels positioned at a height of 6.55 m above the floor, along the two sides of the chapel.
3. The third configuration (Fig.3), "Case 2", involves a dry radiant floor system for radiant heating/cooling, complemented by eight vents for an air inlet situated at the level of the floating floor.

To appropriately size the ventilation system, a minimum airflow rate of 20 m^3/h per person was considered, as stated by Standard UNI 10339 for theatres and conference rooms. Given that the chapel is designed to accommodate 80 people, this corresponds to a minimum of 1600 m^3/h. However, the design flow rate was increased to 2000 m^3/h to provide a higher contribution to heat load controlling.

The sensible cooling load in the summer is estimated at approximately 12.7 kW. This value was calculated by summing various contributions: the thermal load from people present in the room (80 people x 100 W each, totaling 8 kW), lighting (24 lights x 165 W each x 0.7, totaling about 2.7 kW), estimated electrical equipment at about 1 kW, and transmission load calculated as 1000 W. The sum of these contributions provides a total sensible cooling load of approximately 12.7 kW. Latent loads (and the inlet humidity of the primary air) are not relevant for this study.

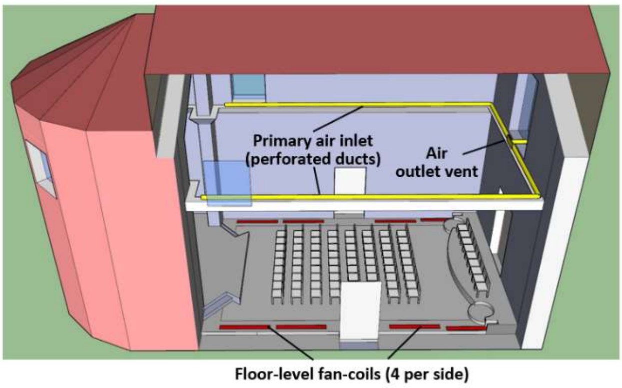

Fig. 2. DesignBuilder 3D Model – Case 1

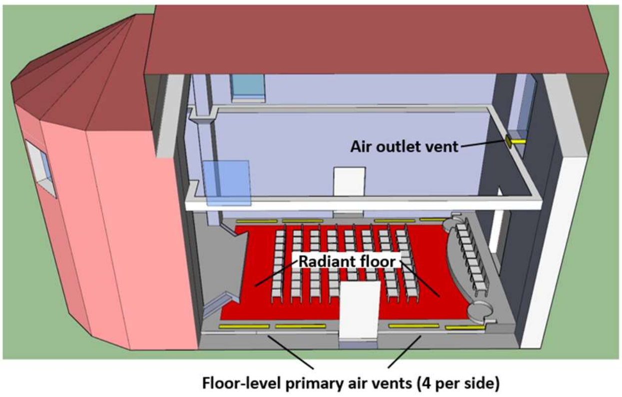

Fig. 3. DesignBuilder 3D Model – Case 2

In "Case 1", the fan coils, located along the perimeter of the floor area, operate with an airflow rate of 500 $m^3 \cdot h^{-1}$ each, releasing air at 25 °C in winter and 20 °C in summer. Conversely, the ventilation channels release an overall air flow rate of 2000 $m^3 \cdot h^{-1}$ at a temperature of approximately 20 °C in both winter and summer.

In "Case 2", the dry radiant floor maintains a surface temperature of 26 °C in winter and 21 °C in summer. Each floor-level air vent introduces an air flow rate of 250 $m^3 \cdot h^{-1}$ at a temperature of 20 °C in winter and 16 °C in summer. The difference in the inlet temperature of the ventilation rate between the two cases is attributed to the limited heating and cooling capacity of the radiant floor, necessitating a further contribution to the sensible load by the primary air. This results in an inlet temperature that is 10 °C below the indoor set point temperature in the summer. On the other hand, in "Case 1", the fan coils provide a significant contribution to meeting the comfort conditions, and the primary air inlet temperature aligns with the indoor temperature in winter (20 °C).

Finally, the simulations for the calculation of comfort conditions were conducted considering a relative humidity of 55% and a metabolic activity equivalent to 1 met (representing sedentary activity). As for the clothing index, a value of 1 clo was assigned for a typical winter day (23rd December), and 0.5 clo for a typical summer day (1st July).

3. Results and Discussion

3.1 Air velocity distribution

The results presented in this section and the subsequent subsections are based on simulations conducted for a typical winter day (23rd December) and a typical summer day (1st July), specifically at 21:00.

This specific time was chosen as it typically coincides with the scheduling of museum exhibitions or evening theatre performances.

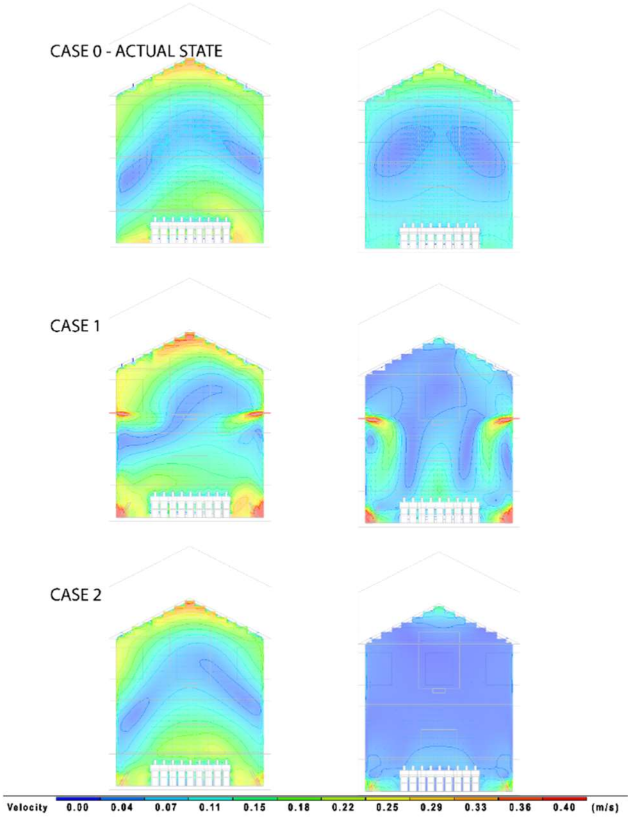

Fig.4. Air velocity distribution on 23rd December (left column) and 1st July (right column) at 21:00.

On the other hand, the selection of these days was based on a comprehensive statistical analysis of long-term local climate data that identified these as typical winter and summer days, respectively.

During the simulated winter day, as depicted in Figure 4, the air velocity near the occupants in "Case 0" is approximately 0.15 m·s^{-1}. In contrast, it is about 0.10 m·s^{-1} in "Case 1" and 0.15 m·s^{-1} in "Case 2". A noteworthy observation from these simulations is that in "Case 1", the fresh air does not exhibit a strong tendency to move towards the occupants.

However, in "Case 2", the ventilation proves to be more effective, with the fresh air easily reaching all the occupants. On the simulated summer day, the air velocity near the occupants in "Case 0" is about 0.05 m·s^{-1}, while it is about 0.15 m·s^{-1} in "Case 1" and 0.10 m·s-1 in "Case 2". Interestingly, both "Case 1" and "Case 2" demonstrate an effective ventilation pattern. In fact, during the summer, the fresh air in "Case 1" tends to move towards the occupants, a phenomenon attributed to the higher density of cold air compared to hot air. These simulations provide valuable insights into the thermal dynamics of the building under different scenarios and seasons, contributing to the development of energy-efficient solutions that ensure optimal comfort for occupants.

3.2 Air temperature distribution

Figures 5 and 6 illustrate the air temperature distribution at 21:00 on a typical winter day and a typical summer day, respectively. These figures represent two cross-sections, cut in the middle of the audience-occupied zone. The numerical values reported correspond to a vertical line positioned 50 cm ahead of the first row of occupants, but the analysis also considers the temperature distribution inside and above the occupied zone.

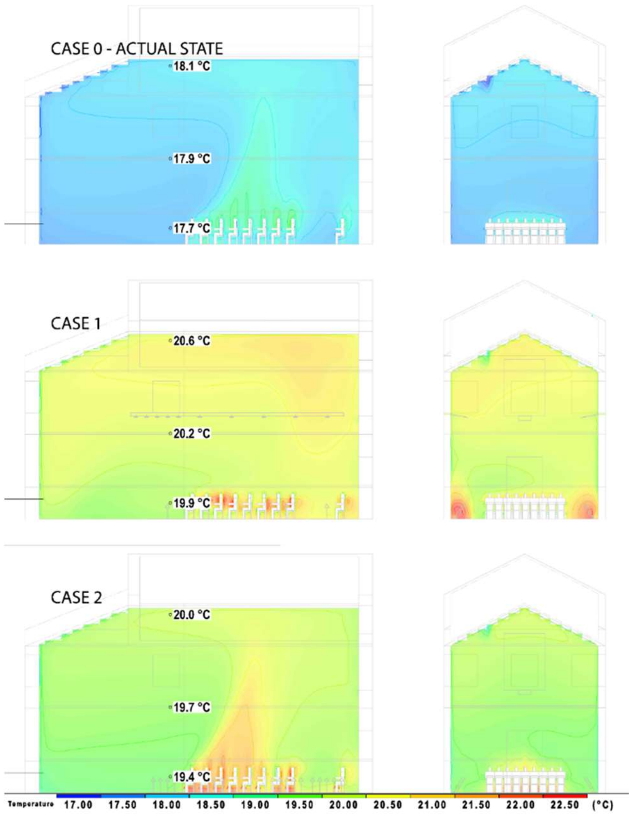

Fig.5. Air temperature distribution on a typical winter day (23rd December at 21:00).

On the typical winter day (Figure 5), "Case 0" shows a limited thermal stratification with air temperatures ranging from 17.7 °C in the lower part of the chapel to 19.0 °C near the occupants. In contrast, "Case 1" exhibits higher temperatures, up to 22.3 °C near the occupants, due to the use of a convective terminal. "Case 2", which employs aradiant floor, maintains moderate temperatures, with a maximum of 21.5 °C near the occupants.

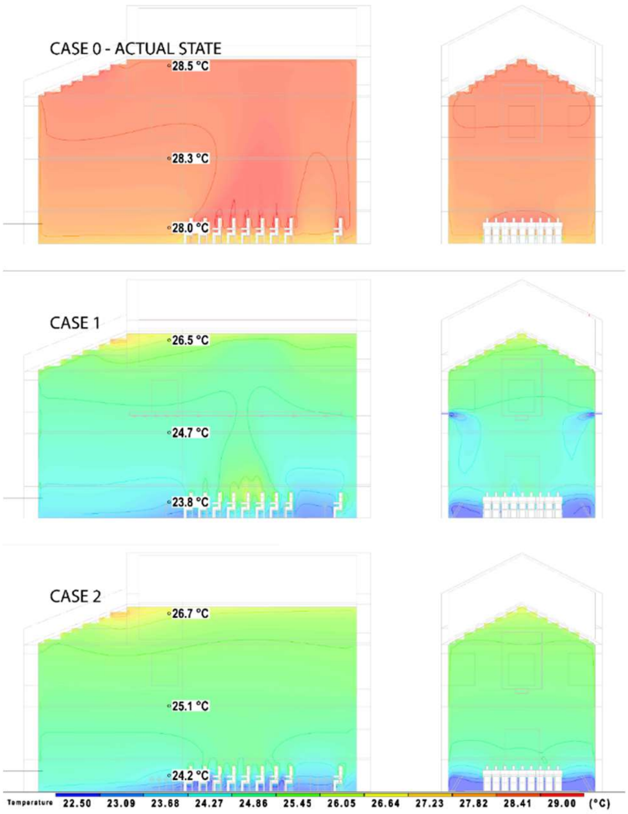

Fig.6. Air temperature distribution on a typical summer day (1st July at 21:00).

Regarding the typical summer day, Figure 6 indicates indicates potential discomfort with temperatures reaching 29.0 °C near the occupants. Both “Case 1” and “Case 2” reduce this effect, with “Case 1” showing partial cooling even in the upper layers of the chapel.
However, “Case 2” maintains slightly warmer top layers, indicating less pronounced thermal stratification.

3.3 PMV distribution

Figure 7 illustrates the PMV (Predicted Mean Vote) values at 21:00 on a typical winter day (depicted on the left) and a typical summer day (depicted on the right).
In “Case 0”, the PMV falls outside the optimal range of -0.50 to 0.50 during both winter and summer. It typically hovers around PMV = -1 (indicating slight coolness) in winter and PMV = 1 (indicating slight warmth) in summer. This study primarily focuses on the analysis of building usage during evening theatre performances. However, simulations were also conducted at 11:00 on the same days to better understand the daily evolution of comfort conditions. During winter, the PMV value in the former chapel at 11:00 is nearly identical to the value at 21:00. Conversely, on a summer day, the PMV value at 11:00 is approximately +1.2. In contrast, for both “Case 1” and “Case 2”, the PMV falls within the optimal range of -0.50 to 0.50 and is very close to 0, indicating thermal neutrality. Therefore, in both cases and at both times of use, thermal comfort is effectively maintained by both technical system configurations.
The most noteworthy finding from the simulations is that “Case 2” provides the same level of thermal comfort as “Case 1”. This is despite the air temperature being slightly higher in summer or lower in winter compared to a fan-coil system, and lower thermal stratification being observed. This suggests that “Case 2” could be a viable alternative for maintaining thermal comfort.

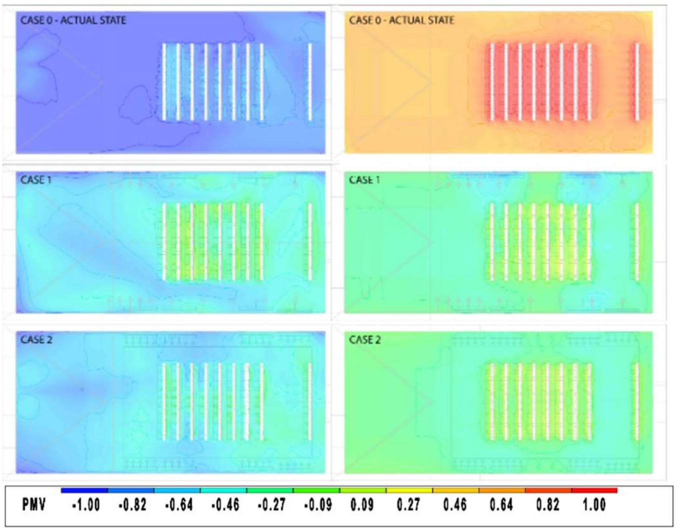

Fig.7. PMV distribution on 23rd December (left column) and 1st July (right column) at 21:00.

4. Conclusions

This research has investigated the thermal comfort and stratification in a former chapel, which is being renovated for use as either a conference room or a small concert hall. The study examines the current configuration without thermal systems and two potential HVAC system configurations: floor-level convective heating (“Case 1”) and radiant heating (“Case 2”). Both configurations ensure an adequate ventilation rate. However, in “Case 1”, air diffusion occurs at a height of 6.55 m above the floor, while in “Case 2”, fresh air is distributed at floor level (underfloor air distribution).
The study discovers that both a convective system (“Case 1”) and a radiant floor system (“Case 2”) can provide comparable levels of thermal comfort. However, several factors favour the radiant floor system as detailed as follows:

- While both configurations ensure effective air renewal in the summer, this is not the case in the winter.
  The radiant floor system provides better air distribution during the winter months compared to the convective system. In the convective system, the air inlet at 20 °C at a height of 6.55 m does not allow a descending flow towards the occupants due to the lower density of warm air.
  This issue is not present in the radiant floor system, where the same air flow rate is distributed near the floor.
- The radiant floor system is typically more energy-efficient. For instance, in winter, the radiant floor can be supplied with water at a lower temperature (around 35 °C for supply flow and 30 °C for return flow) compared to the fan coils in “Case 1”, which require water at approximately 50 °C.
  This results in lower heat losses in the water distribution pipes in the radiant floor system, and it also allows for

the production of hot water with a heat pump that operates with a higher Coefficient of Performance (COP).
Additionally, the radiant floor system does not require auxiliary electricity-driven fans, unlike the fan coils in "Case 1".

- The radiant floor system is also more energy-efficient in the summer months, as it cools only the air at lower altitudes rather than the entire volume of the building. In contrast, "Case 1" cools the entire volume of the building, leading to energy waste.

Future studies aim to extend the monitoring period to include some summer days and optimize the thermal system configuration and operation.
This research provides valuable insights into the potential benefits of radiant floor systems in similar renovation projects.

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