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ORIGINAL ARTICLE

Climate resilience strategies for schools in mediterranean areas: is it feasible to condition air merely with ventilation?

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Abstract Managing energy costs in school buildings across Italy poses a significant challenge. Over time, various directives have aimed to reduce energy consumption and improve indoor air quality to enhance student and teacher performance. This study offers an innovative analysis of the thermal behavior of a school in a typical Mediterranean climate. The building envelope is designed to meet legal standards for thermal transmittance specific to its Italian climate zone. Using Termolog Epix 15 software, the study conducts dynamic annual and hourly simulations to assess operative temperature and relative humidity in classrooms, with the heating system turned off and varying air exchange rates. The results suggest that optimizing the building envelope can be more effective than installing traditional HVAC systems (heating, ventilation, and air conditioning) in warm climates, demonstrating the effectiveness of a mechanical ventilation system without heating or cooling. By analyzing the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices, the study demonstrates that it is possible to maintain acceptable thermo-hygrometric comfort through the only ventilation. During winter, with air changes per hour ranging from 1 to 5, classrooms can maintain temperatures between 21 °C and 23 °C, ensuring thermal comfort without heating. Typically, a heating system would operate for approximately 1071 h annually, excluding holidays. However, an effective ventilation system could eliminate the need for heating entirely. While maintaining optimal temperatures in the intermediate months (spring/autumn) and summer is more challenging, this concern is mitigated by the fact that schools are closed during summer holidays.

Keywords Schools · Indoor Thermal comfort · Internal Temperature Operative · Mechanical Ventilation · Air Changes

Introduction

School buildings, which account for a significant part of the building stock, are responsible for a high level of energy consumption within the non-industrial energy consumption of a country (Barbhuiya and Barbhuiya 2013). Among all public buildings, school buildings, because of their educational function, bear a significant social responsibility. Educational

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facilities represent a key field for the implementation of sustainability practices and energy efficiency programs. For this reason, several energy efficiency plans have been developed globally to improve the energy performance of school buildings.

Al Faris et al. (2016) analyzed an energy management program as a sustainable strategy applicable to schools. Ambient air quality is an essential part to consider during the design and management phases (Burman et al. 2014, Pereira et al. 2014). Classrooms must provide high levels of thermal, visual and ventilation comfort (Jovanović et al. 2014, Wang et al. 2014). In addition, considering that energy cost is one of the major operational expenses of buildings, efficiency and sustainability of systems play a crucial role in promoting economic progress, improving social life, and increasing students awareness of sustainability.

Because of the high occupant density in classrooms and the negative influence that an unsatisfactory thermal environment can have on student learning and performance, comfort conditions for school buildings have always been critical (Barrett et al. 2015). Low ventilation rates negatively affect teaching and learning, significantly reduce student attention and alertness and impairing memory and concentration (Bakó-Biró et al. 2012). A later analysis quantitatively demonstrated that inadequate conditions in classrooms can reduce children performance by up to 30 percent (Wargocki and Wyon 2013).

Sánchez et al. (Sánchez et al. 2023) proposed a deep building energy retrofit strategy for Mediterranean schools, highlighting how intervention on solar shading systems is crucial to balance cooling demand.

Campagna et al. (2023) explored the factors influencing heating consumption in schools in Mediterranean climates, providing for the first time a comprehensive assessment of the school building stock in Puglia, involving more than 1000 kindergartens, primary and secondary schools. Most schools in Puglia (46.2%) were built before 1976, without energy regulations, while a significant percentage (44%) date from 1976–1992. The monthly consumption profile shows the highest values in the months from November to March, when both heating and electricity are present. In general, heating consumption dominates, exceeding electricity consumption up to three times.

Students spend a significant amount of time in school, making it essential to ensure comfortable thermal conditions within these buildings. Thermal comfort, being closely linked to productivity, well-being, and energy conservation in schools, has gained increasing importance in recent years. Zomorodian et al. (2016) provided an overview of thermal comfort investigations in school buildings over the past fifty years. Ventilation has been highlighted in most studies as a key determinant of indoor air quality and thermal comfort. Maintaining good Indoor Environmental Quality (IEQ) in UK schools, in terms of overheating and air quality, is critical for children health and academic performance. Improving the energy efficiency of school buildings is also a central component of the UK carbon reduction strategy (Karakas et al. 2023).

Ashrafian (2023) analyzed the interaction between climate change and building performance, focusing primarily on energy consumption, economic implications, and occupant comfort. The study examined the impact of future climatic conditions on school buildings in various climates, analyzing energy, economic, and comfort aspects. The findings reveal that in warmer climates, there is potential for nearly doubling primary energy consumption, overall costs, and CO_2 emissions in the future.

Indoor space ventilation in buildings can be achieved through two main approaches: a passive and an active one. Natural ventilation, a passive system, takes advantage of natural forces such as wind and thermal buoyancy, but its efficiency depends largely on external weather conditions and the behavior of occupants adjusting the ventilation rate. In contrast, mechanical ventilation ensures constant air exchange through the use of active systems (Maiques et al. 2024, Wood et al. 2024).

Several studies have shown that multiple health problems are related to poor indoor air quality and that the economic value of a building can suffer depreciation when it is recognized that air quality performance is unsatisfactory (Marzouk & Atef 2022). The installation of mechanical ventilation systems, in enclosed spaces, allows for a controlled increase in ventilation rates and a reduction in CO_2 concentrations (Cabovská et al. 2022). In addition, ventilation is an effective measure to mitigate the risk of airborne transmission of respiratory diseases (Rawat & Kumar 2024).

For public authorities, improving the energy efficiency of public buildings is not only an important goal but also an opportunity. Before defining a strategy, authorities need to consider some key issues: the difference in energy performance between new and existing school buildings, the best technical solutions for energy upgrades and most importantly, the economic efforts needed to support energy renovations (Dall'O' and Sarto 2013). Studies (Congedo et al. 2016, Zacà et al. 2016) have shown how the optimal cost methodology is useful in seeking the most appropriate upgrading measures for energy retrofitting of existing public buildings. In school buildings, it is critical to achieve a balance between reducing operating costs and maintaining a high level of comfort, as this not only optimizes student performance but also directly affects crucial aspects such as learning (Wargocki et al. 2020), school performance, health (Carrer et al. 2015), teacher productivity, and overall satisfaction (Wargocki & Wyon 2017). Thus, adequate indoor ventilation and good air quality are key elements in ensuring such overall benefits (Andamon et al. 2023).

The results of (Baglivo 2021) showed that discomfort in school buildings in hot climates could increase over the years, even in the post-intervention phase. Overheating leads to the need to implement cooling and mechanical ventilation systems, which due to the pandemic are becoming increasingly important to ensure healthy indoor air. This will lead to increased demand for electricity, with significant implications for energy and environmental policies nationally and internationally. In the future, the operative temperature of classrooms will increase, the thermal performance index for heating will decrease, and the thermal performance index for cooling will increase, leading to an increase in overall annual building demand.

Regarding lighting, a school is a highly complex environment, as it consists of many areas with different uses and, therefore, different needs. Optimizing lighting in a school means enabling students and staff to perform their visual activities to the fullest without visual fatigue. Results show a 33 percent reduction in energy consumption by simply replacing fluorescent fixtures with LEDs. In addition, adjusting the intensity of LED lamps in rows of fixtures leads to a 95% reduction in energy consumption compared to the current state (Baglivo et al. 2021).

In conclusion, school buildings offer an important opportunity to integrate technological solutions and sustainability strategies, helping to meet future energy and environmental challenges.

Expected research outcomes

The objective of the work is to investigate the possibility of non-use of the heating system in schools, while maintaining tolerable comfort levels, during winter in warm climates. The starting idea is that, for a school with an efficient building envelope, the winter heating requirements can be easily covered by internal heat loads, especially those due to people and equipment. It is possible to think of controlling the operative temperature by acting on the ventilation flow rate. Thus, the heat demand of the room is balanced, by varying the mass flow rate, according to the temperature of the outside air input. A cross-flow heat recovery unit, with bypass and free-cooling options, allows the control margins to be expanded.

To adjust the operative temperature using the ventilation flow rate in winter, the following principles are adopted:

- Increasing the ventilation flow rate to lower the temperature: If the goal is to reduce the temperature in a room, increasing the ventilation flow rate can help remove accumulated heat more quickly. This is because more fresh outside air is introduced while warmer indoor air is exhausted.
- Reducing ventilation flow rate to increase temperature: Conversely, if the goal is to increase temperature, reducing ventilation flow rate can help limit heat loss. With less air movement, heat transport from the inside to the outside is reduced, helping to maintain or increase the indoor temperature. By varying the rotation speed of the fans, the mass flow rate of air entering and leaving the room can be controlled. Variable-speed fans allow more precise adjustment of the operative temperature, adapting better to the specific needs of the environment.
- Use of heat recovery systems: In more complete ventilation systems, a heat recovery system can be included that captures heat from the exhaust air to preheat the incoming fresh air. This significantly improves the energy efficiency of the ventilation system, allowing temperature regulation while reducing significant energy waste. It is always possible to use a by-pass system if exclusion of the

heat exchanger is convenient under certain operating conditions.

- Automation and sensors: The use of temperature sensors and automatic control systems enables more precise and responsive management of operative temperature. These systems can automatically adjust the ventilation rate based on changes in indoor or outdoor temperatures.

However, it is important to note that managing operative temperature through ventilation flow rate alone may present limitations, especially in environments with high indoor heat loads or extreme weather conditions. In such cases, the combined use of heating, ventilation, and air conditioning (HVAC) systems may be necessary to maintain comfortable conditions.

This study evaluates the thermal behavior of a prototype school building contextualized in the city of Lecce, typical of a Mediterranean climate. This evaluation is based on the analysis of indoor operative temperature obtained from annual and hourly simulations in dynamic regime, conducted in all classrooms of the school building. The analyses were carried out with the heating system off and with a variable number of air changes. This study shows that in hot climates it is more appropriate to promote interventions aimed at optimizing the building envelope rather than implementing HVAC systems. The analysis of the PMV and PPD indices made it possible to assess the operational margins of average temperature control by operating with ventilation alone, maintaining acceptable indoor thermo-hygrometric comfort conditions.

Methodology

After an initial definition of the building envelope, the methods used to define thermal comfort in an indoor environment with only a ventilation system, possibly equipped with a recuperator, and without an air-conditioning system are introduced.

- Characterization of the building model: A simple, regular geometry was chosen for the school building to ensure the study replicability. The building is assumed to be located in Lecce, in the southeast of Italy, in a typical Mediterranean climate. Its envelope was designed to meet national thermal transmittance limits.
- Characterization of ventilation system: A controlled mechanical ventilation system is planned for the classrooms that can handle an hourly change of 1 to 10 volumes per hour.
- Definition of thermal model: The building model is implemented in Termolog EpiX 15. Operative temperature and indoor relative humidity values are plotted for different ventilation scenarios for all classrooms.
- Analytical determination of thermal comfort: UNI EN 16798–1 standard and UNI EN 7730 are used for the calculation of the thermal comfort for all air changes in each classroom.
- Analysis of the results: Analysis of thermal and comfort results plotted for the entire reference year.

Characterization of the building model

The case study concerns a prototype school building with a square floor plan, divided into nine zones of equal size. This configuration is adopted to simplify the analysis, make the results easily replicable, and ensure that each zone is exposed on all sides.

The analysis of school architecture revealed that the geometry of classrooms is essentially always the same, regular in shape, generally rectangular, with one, at most two walls exposed to the outside with windows on one or both sides, and a wall facing a thermal zone (corridor), which is also heated.

Therefore, for the purposes of calculating the thermal loads of the classrooms alone, which are the object of the study, the simplification does not lead to a loss of calculation detail, limiting the study to classrooms with a high internal load that differs from the other thermal zones typical of a school.

In accordance with Italian Ministerial Decree Dec. 18, 1975 (DM 18 dicembre 1975, Ministro dei lavori pubblici. 1975), with reference to teaching functionality, for an elementary school, the internal area of a classroom is $1.8 \times (\mathrm{m}^2/$ alumnus). Thus, the prototype building has, a square floor plan with a net area of 332.70 m^2 and a net height of 3.00 m. As shown in Fig. 1, the area was divided into nine equally sized modules of 6×6 m^2.

Table 1 presents the thermal transmittance limits in accordance with Ministerial Decree 26/06/2015 (M.D. 26/6/2015, Italian Ministerial Decree.

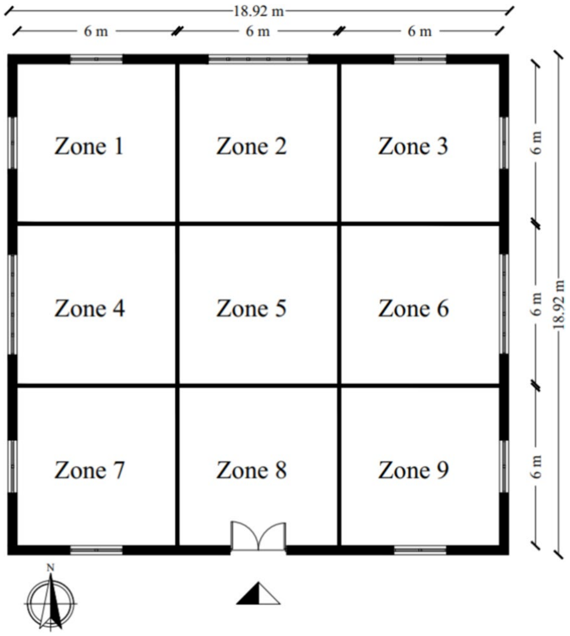


Fig. 1 Floor plan of the school model

2015) for climate zone C, used to set up the model stratigraphy.

Details of the building envelope are shown in Figs. 2, 3, 4 and 5.

Characterization of ventilation system

A controlled mechanical ventilation system is planned for the classrooms that can handle an hourly change of 1 to 10 volumes per hour. Heating/cooling and humidification/dehumidification are not planned.

The objective is to demonstrate that, with a highly efficient envelope, in Mediterranean climate conditions, it is possible to maintain the conditions of internal comfort in the classrooms with only the ventilation system, modulating the loads with only the variation of the flow of air introduced/exhausted. The analyses, under the most critical conditions, do not include a heat recovery unit.

Subsequently, the use of a heat recuperator will add an additional control parameter which is the temperature of the air introduced. It will be possible to exploit pre-cooling or pre-heating of the air by the heat recuperator or decide to bypass it if it is not thermally convenient.

Definition of the building thermal model

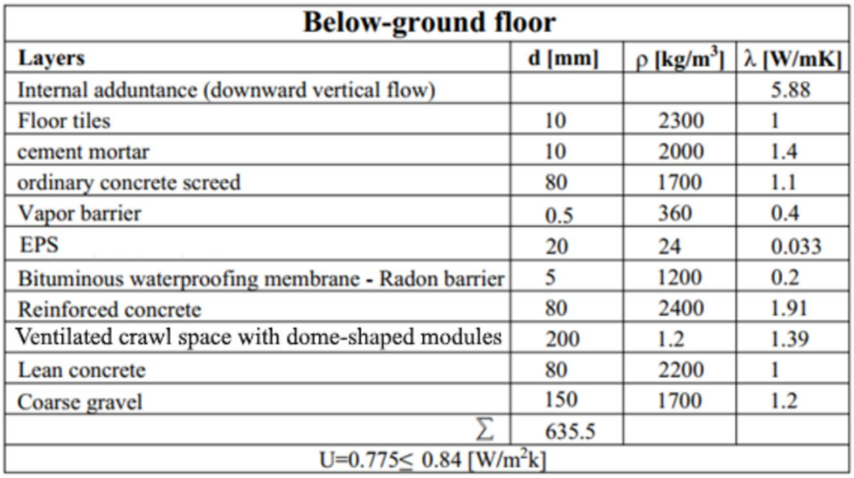
The school is located in Lecce, a city in the Apulia region in southeastern Italy, which falls under national climate zone C. The Italian climate classification is determined in function of the Heating Degree Days (HDD). Specifically, degree days correspond to the sum, extended to all days of the year, of the difference (only the positive one) between the temperature of the indoor environment and the average daily outdoor temperature. Lecce has a typical Mediterranean climate, alternating mild winters, warm springs, torrid summers and hot autumns; precipitation is almost always less than 500 mm. According to international classification, such as Koppen's climate classification (Arnfield 2023), Lecce is classified as Csa, warm-summer Mediterranean climate.

The annual outdoor temperature trend is shown in Fig. 6. Highlighted in orange are the periods when the school is not in use for school vacations.

The building model is implemented in Termolog EpiX 15 (Logical Soft, Termolog 2022), a widely used and appreciated tool in Italian design and research, as demonstrated by recent studies (Congedo et al. 2021a, Baglivo et al. 2022, Congedo et al. 2020, Costa et al. 2024, Congedo et al. 2021b, Fregonara et al. 2017, UNI EN ISO 52016-1:2018 2018). This modular energy analysis software, certified by the Comitato Termotecnico Italiano (CTI),

Table 1 Thermal transmittance limits in compliance with M.D. 26/06/2015 for the climate zone C

Italian climate zones	Heating on		Envelope components	U [W/m^{2}K]
	From 1993	From 2022		
C $900 < HDD \leq 1400$	November 15—March 31 (10 h a day)	November 22-March 23 (9 h a day)	U_{roof} U_{wall} U_{floor} U_{window}	0.33 0.34 0.38 2.20



Below-ground floor

Layers	d [mm]	ρ [kg/m³]	λ [W/mK]
Internal adduntance (downward vertical flow)			5.88
Floor tiles	10	2300	1
cement mortar	10	2000	1.4
ordinary concrete screed	80	1700	1.1
Vapor barrier	0.5	360	0.4
EPS	20	24	0.033
Bituminous waterproofing membrane - Radon barrier	5	1200	0.2
Reinforced concrete	80	2400	1.91
Ventilated crawl space with dome-shaped modules	200	1.2	1.39
Lean concrete	80	2200	1
Coarse gravel	150	1700	1.2
∑	635.5		
U=0.775≤ 0.84 [W/m²k]			

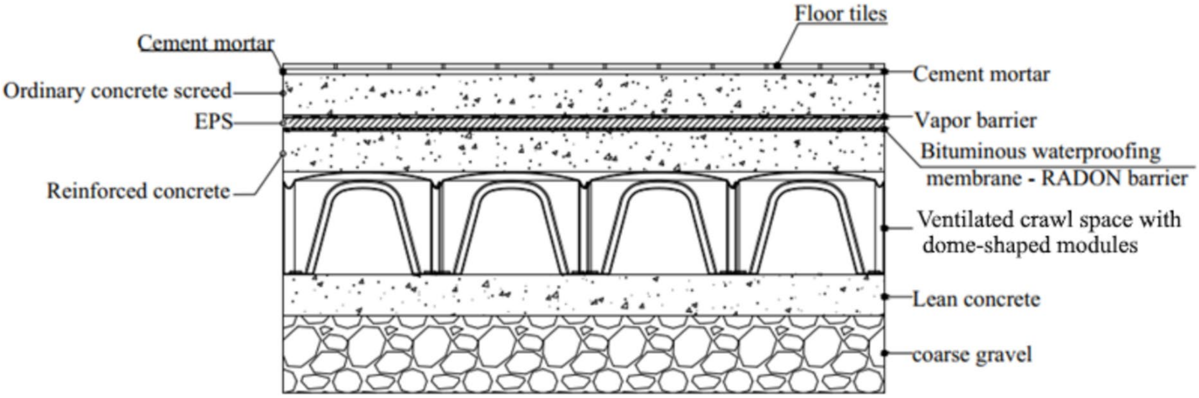
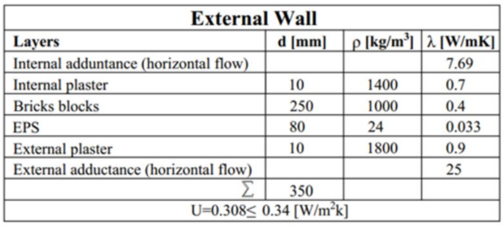


Fig. 2 Below-ground floor stratigraphy



External Wall

Layers	d [mm]	ρ [kg/m³]	λ [W/mK]
Internal adduntance (horizontal flow)			7.69
Internal plaster	10	1400	0.7
Bricks blocks	250	1000	0.4
EPS	80	24	0.033
External plaster	10	1800	0.9
External adductance (horizontal flow)			25
∑	350		
U=0.308≤ 0.34 [W/m²k]			

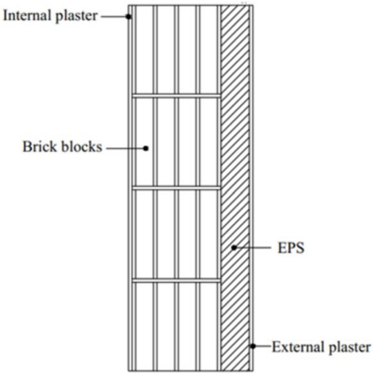
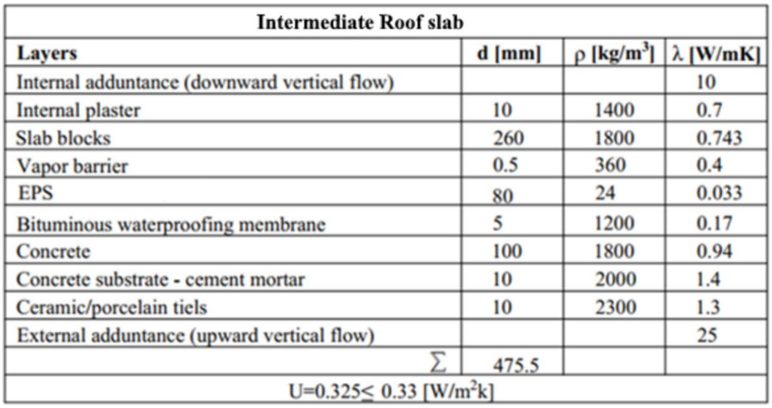


Fig. 3 External wall stratigraphy

is equipped with an hourly dynamic calculation engine. It performs hourly energy balance evaluations, accurately reflecting the building response to external and internal climatic conditions, in accordance with UNI EN ISO 52016 (Congedo et al. 2021b).

Each zone of the school prototype represents a classroom, each capable of accommodating up to 20



Intermediate Roof slab			
Layers	**d [mm]**	**ρ [kg/m³]**	**λ [W/mK]**
Internal adduntance (downward vertical flow)			10
Internal plaster	10	1400	0.7
Slab blocks	260	1800	0.743
Vapor barrier	0.5	360	0.4
EPS	80	24	0.033
Bituminous waterproofing membrane	5	1200	0.17
Concrete	100	1800	0.94
Concrete substrate - cement mortar	10	2000	1.4
Ceramic/porcelain tiels	10	2300	1.3
External adduntance (upward vertical flow)			25
Σ	475.5		
U=0.325≤ 0.33 [W/m²k]			

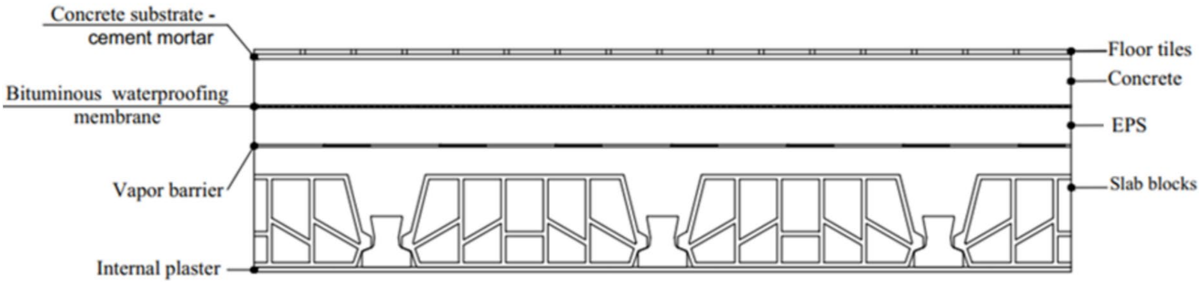


Fig. 4 Intermediate Roof slab

students. Educational activities are scheduled from Monday to Friday, 8:00 a.m. to 4:00 p.m., and the ages of students range from 6 to 10 years old.

The values of operative temperature and indoor relative humidity are measured for the different air changes indicated as 'Combo' followed by the corresponding number of air changes. For example, in Combo 01 the operative temperature values are obtained by ensuring only one air volume change per hour, while in Combo 02 the operative temperature values occur with two air volume changes per hour and so on. For each classroom, the study combinations include a minimum of 1 up to a maximum of 10 air volume changes. The number of students in the room was kept constant.

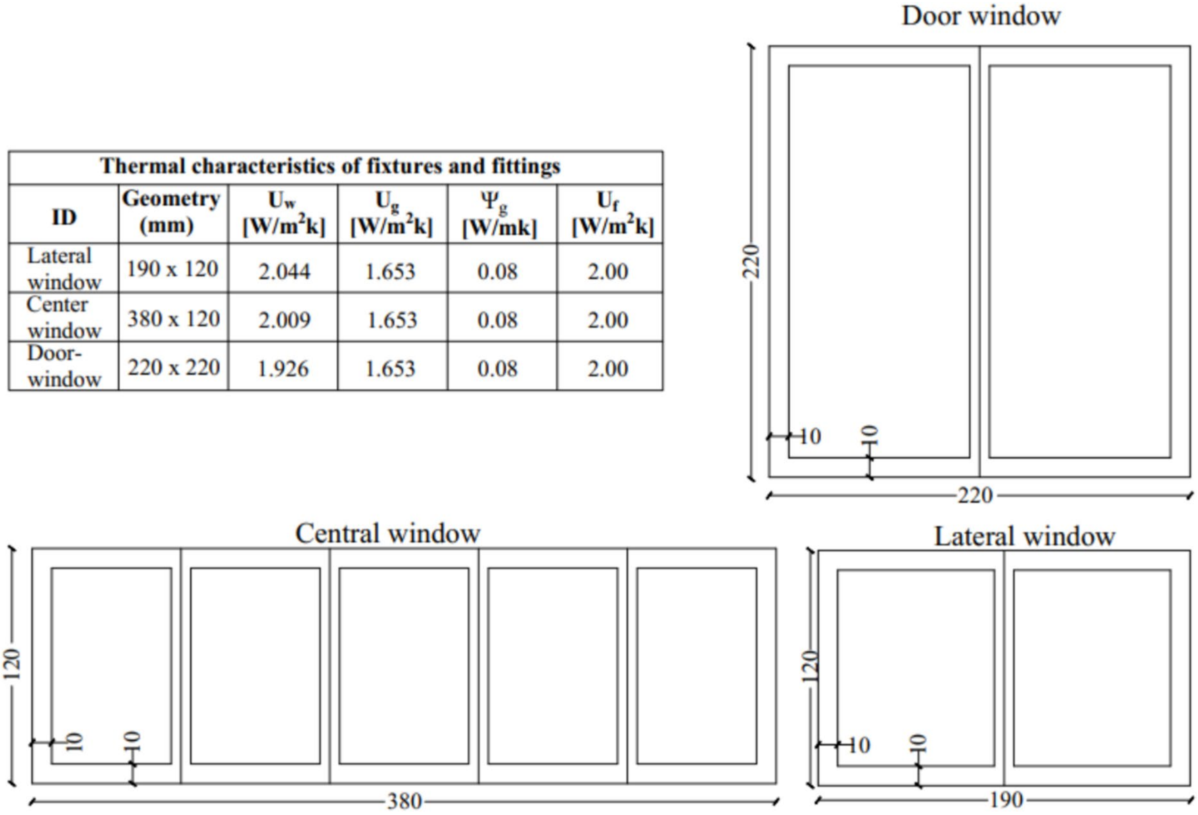
According to the Italian Ministerial Decree of December 18, 1975 (DM 18 dicembre 1975, Ministro dei lavori pubblici 1975), the minimum number of air exchanges per hour for a school with children aged 6 to 10 is 2.5 vol/h. Air changes below 2 vol/h are designed to assess temperature trends in extreme cases.

Analytical determination of thermal comfort

Thermal comfort is assessed in accordance with UNI EN 16798–1:2019 (UNI EN 16798–1:2019 2019), which considers four indoor environment quality categories, namely High, Moderate, Medium and Low. The school falls into the high category.

The UNI EN 16798–1 standard is also applicable to buildings without air-conditioning systems, but only equipped with ventilation (mechanical or natural, or a combination of both). This standard provides guidelines for the design and assessment of indoor environmental conditions (thermal comfort, air quality, lighting and acoustics) in buildings intended for non-industrial use.

However, some clarification is necessary since in the winter season the operative temperature be within a range of 21 °C to 23 °C, while in the intermediate (spring/autumn) and summer seasons the thermal comfort zone of the indoor operative temperature varies according to the two Eqs. (1)



Thermal characteristics of fixtures and fittings					
ID	**Geometry (mm)**	**U_w [W/m²k]**	**U_g [W/m²k]**	**Ψ_g [W/mk]**	**U_f [W/m²k]**
Lateral window	190 x 120	2.044	1.653	0.08	2.00
Center window	380 x 120	2.009	1.653	0.08	2.00
Door-window	220 x 220	1.926	1.653	0.08	2.00

Fig. 5 Thermal characteristics of fixtures and fittings

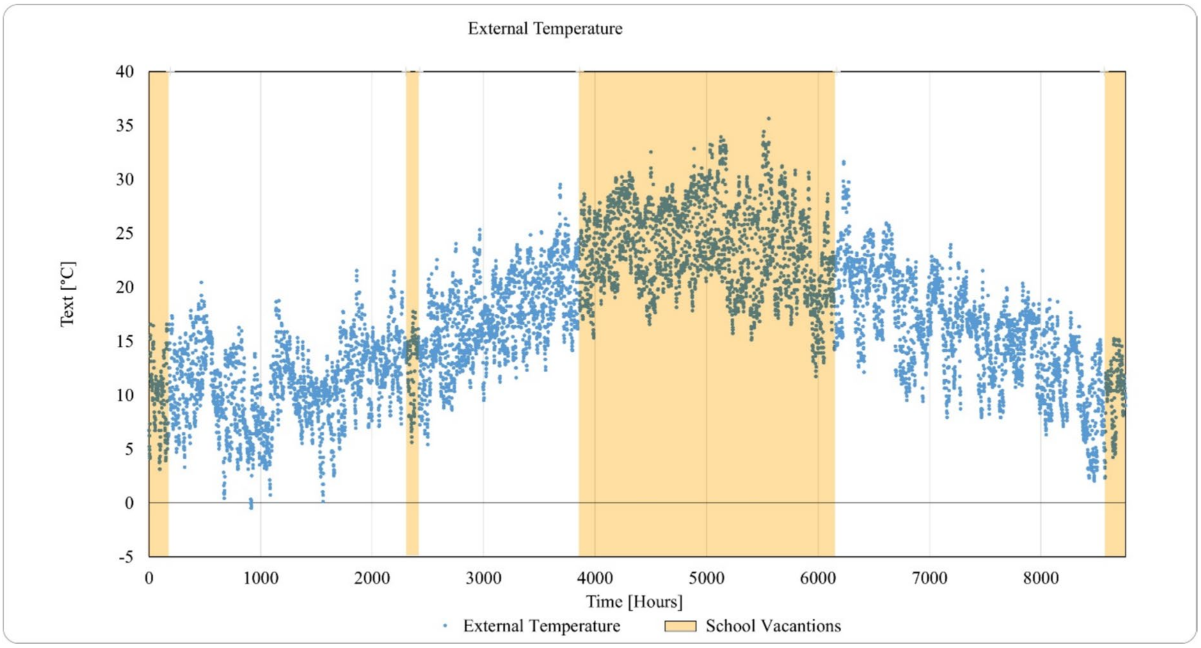


Fig. 6 Annual External Temperature (UNI 10349–1:2016 (2016)

expressed in the standard for the quality category of the environment under consideration.

$$\text{category I: } \begin{cases} \theta_0 = 0.33 \bullet \theta_{rm} + 18.8 + 2 \textit{ Upper limit} \\ \theta_0 = 0.33 \bullet \theta_{rm} + 18.8 - 2 \textit{ Lower limit} \end{cases} \quad (1)$$

where:

- θ_0 is indoor operative temperature [°C]
- θ_{rm} is weighted average external temperature [°C].

Next, this study assesses thermal comfort in accordance with UNI EN 7730 (UNI EN ISO 7730:2006 2006), which provides criteria and procedures for this assessment through the calculation of PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied).

The use of UNI EN ISO 7730 facilitates comparison with other air-conditioned buildings, creating a uniform basis for evaluation and demonstrating how thermal comfort can be guaranteed even without active cooling systems. The application of UNI EN ISO 7730 to mechanically ventilated classrooms, possibly with heat recovery, is justified by the standard ability to provide a detailed and quantitative analysis of thermal comfort, exploiting the parameters controllable by the ventilation system. Even in the absence of air conditioning, the system with heat recovery ensures sufficiently stable conditions for the effective use of the PMV/PPD model, providing a useful tool for designing and optimising occupant comfort.

PMV is a numerical measure of thermal comfort based on a mathematical model that considers various factors such as indoor temperature, more precisely defined as indoor air temperature (Ta) or indoor dry-bulb temperature, mean radiant temperature (MRT), relative humidity (RH), air velocity, occupant clothing, and physical activity level. Values near zero indicate optimal comfort, while positive values indicate an environment that is too warm and negative values indicate an environment that is too cold. The PMV scale ranges from −3 to + 3.

The PPD index indicates the percentage of people expected to be dissatisfied with thermal comfort. This measure takes into account individual differences in tolerance to heat or cold. PPD values above 20% indicate a significant level of thermal dissatisfaction, while values below 10% indicate good thermal comfort.

Results and discussions

The study follows the guidelines set out in the UNI EN 16987–1 and UNI EN 7730 standards for evaluating thermal comfort in buildings without heating or cooling systems, considering the specific criteria for buildings with mechanical ventilation systems.

This section reports the results obtained through dynamic simulations, considering the heating system turned off. The results are reported in the following section:

- Variations in Indoor operative temperature Across Zones: A Comprehensive Analysis (Sect. "Variations in Indoor operative temperature Across Zones: A Comprehensive Analysis")
- Assessing Thermal Comfort in a Specific Zone in Accordance with UNI EN 16987 (Sect. "Assessing Thermal Comfort in a Specific Zone in Accordance with UNI EN 16987")
- Yearly Trends in Relative Humidity in a Specific Zone (Sect. "Yearly Trends in Relative Humidity in a Specific Zone")
- Assessing Thermal Comfort in a Specific Zone in Accordance with UNI EN 7730 (Sect. "Assessing Thermal Comfort in a Specific Zone in Accordance with UNI EN 7730")

Variations in indoor operative temperature across zones: a comprehensive analysis

This section thoroughly analyzes the yearly operative temperature trends across all school zones. Hourly assessments were conducted, factoring in various air change scenarios. Supplementary Data contains the complete results. Each classroom corresponds to one thermal zone. The Excel file is organized into separate worksheets labeled "Zone," each dedicated to the indoor operative temperature data of a specific classroom, from the first to the ninth, considering all Combo. Figures 7, 8 and 9 graphically depict the annual variation in classroom operative temperature. Orange highlights indicate periods of school vacation.

Considering Combo 01–05, the results of the operative temperature show that during the coldest periods, as the combinations vary, it is possible to guarantee an adequate operative temperature for thermal comfort (between 21 °C and 23 °C) in the

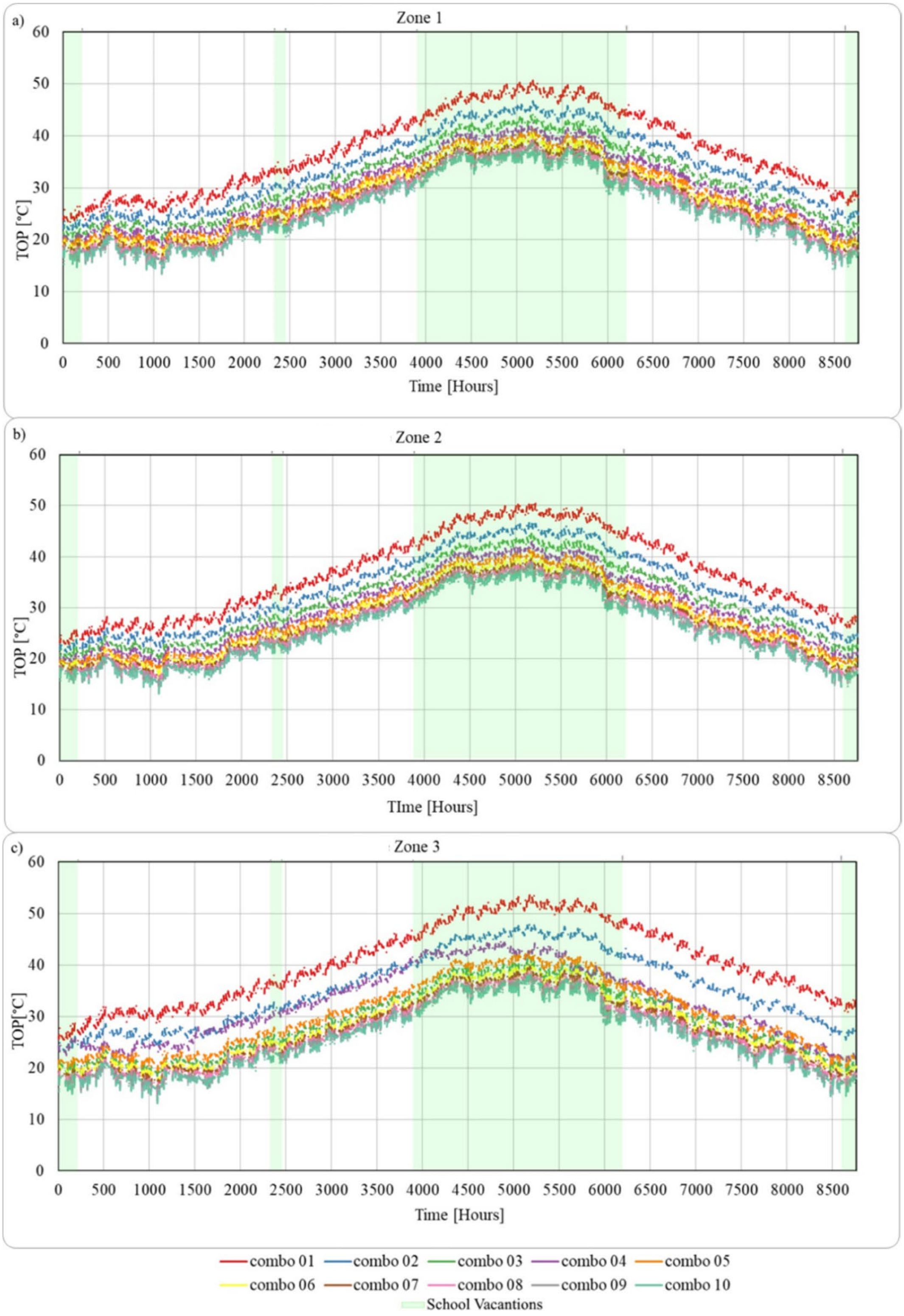


Fig. 7 Indoor operative temperature (TOP) **a)** Zone 1, **b)** Zone 2 and **c)** Zone 3 (number of combo correspond to the number of air volume change a hour)

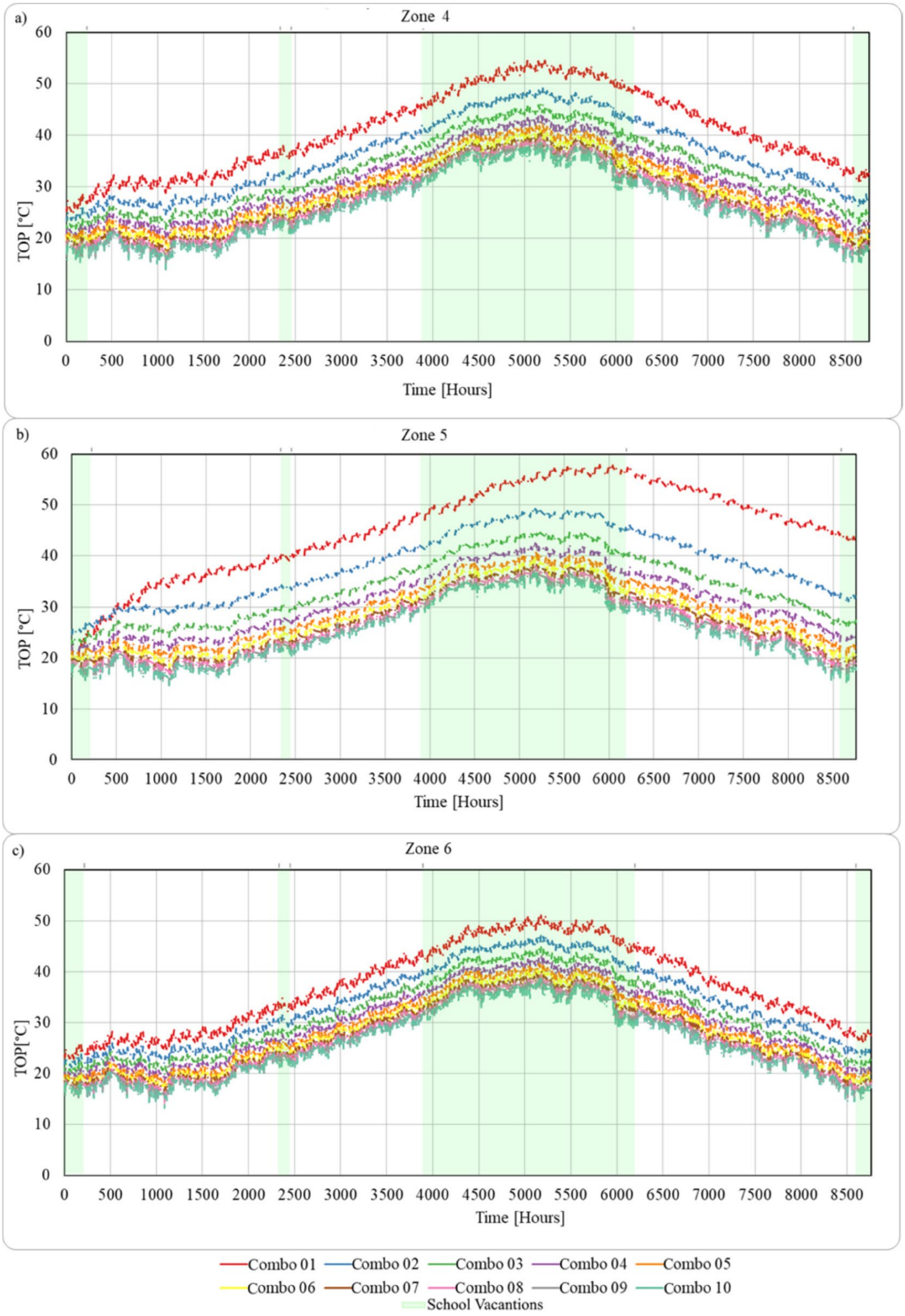


Fig. 8 Indoor operative temperature (TOP) **a)** Zone 4, **b)** Zone 5 and **c)** Zone 6

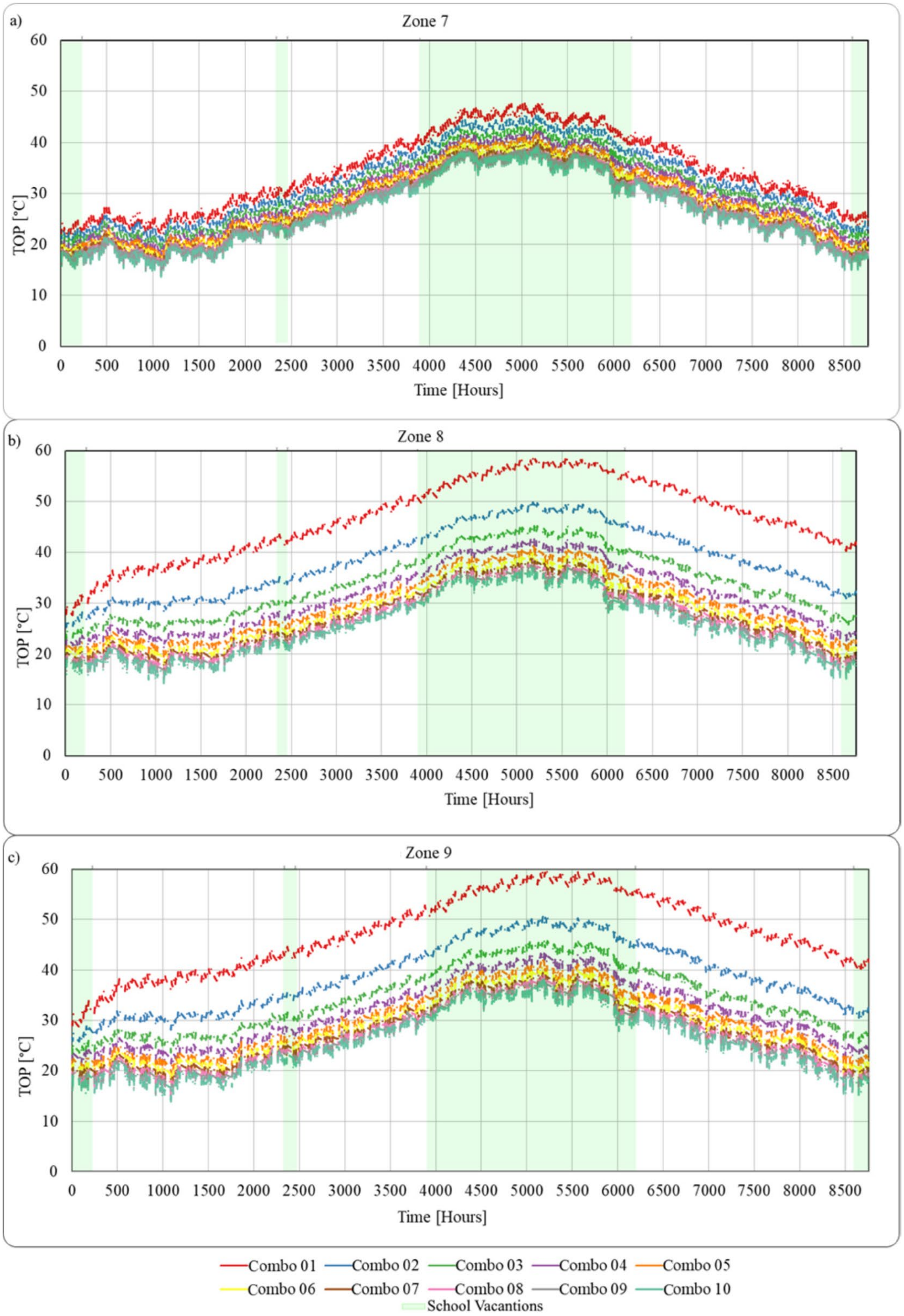


Fig. 9 Indoor operative temperature (TOP) **a)** Zone 7, **b)** Zone 8 and **c)** Zone 9

various classrooms. For example, on the coldest day of the year, which corresponds to the eighth of February (913–936 h), when the outside air temperature reaches a minimum of −0.5 °C (917–918 h), the Combo 01 can be used to maintain an operative temperature of 25.6 °C, keeping the heating off and not varying the number of students.

Besides, it is difficult to guarantee optimal operative temperatures in several zones in the central months of the year and especially in the summer period. In the summer period the problem can be neglected, as schools are closed for the holidays.

Assessing thermal comfort in a specific zone in accordance with UNI EN 16987

The analysis of the thermal comfort was conducted in Zone 7, for example, characterized by a southwest orientation and equipped with two windows, one facing south and the other facing west. Classrooms facing south-west receive direct solar radiation mainly in the afternoon hours.

In the Supplementary Data, the sheet "Study Zone 7" contains data that identify the thermal comfort range according to Eq. (1) in the central months of the year. It also includes tables with values of operative temperature for the coldest days in January, February, March, November, and December, considering the combinations Combo 5 and Combo 3, which allow to stay within the thermal comfort range. Similarly, there are tables with operative temperatures for the hottest days in April, May, June, September, and October, corresponding to the combinations "Combo 05" and "Combo 10".

In the "Combo Zone 7" sheet, tables are reported with operative temperatures on the coldest days of January, February, and March, considering various combinations of air exchanges.

Figures 10, 11, 12 and 13 show the operative temperature trend concerning adaptive thermal comfort, with the comfort zone highlighted in pink. Combo 03 and Combo 05 are plotted for autumn and winter seasons, while Combo 5 and 10 for spring and summer.

In the graphs of Fig. 10, it is evident that by increasing the number of air exchanges, up to a maximum of five room volumes, during the winter months, it is possible to maintain the operative temperature within the adaptive thermal comfort zone.

Looking at Fig. 10a for January, the trend of operative temperatures indicates that Combo 01 and Combo 02 exceed the upper limit of the thermal comfort zone during the observed period. Combo 03 maintains the operative temperature entirely within the thermal comfort zone, ranging from approximately 21.3 °C to 22.4 °C during educational hours. Combo 04 starts below the lower limit of the comfort zone before 10:00 a.m., but gradually reaches the lower limit between 10:00 a.m. and 11:00 a.m. Combo 05 remains above the comfort zone throughout the day.

Looking at Fig. 10b for February, Combo 01 and Combo 02 exhibit similar behavior to January, where the operative temperature exceeds the upper limit of the thermal comfort zone for most of the day. Combo 03 maintains stable temperatures within the comfort zone, ensuring a consistent environment for educational activities. Combo 04 starts below the comfort zone but reaches and stays within the range after 10:00 a.m. Combo 05 remains significantly higher than the upper limit of the thermal comfort zone.

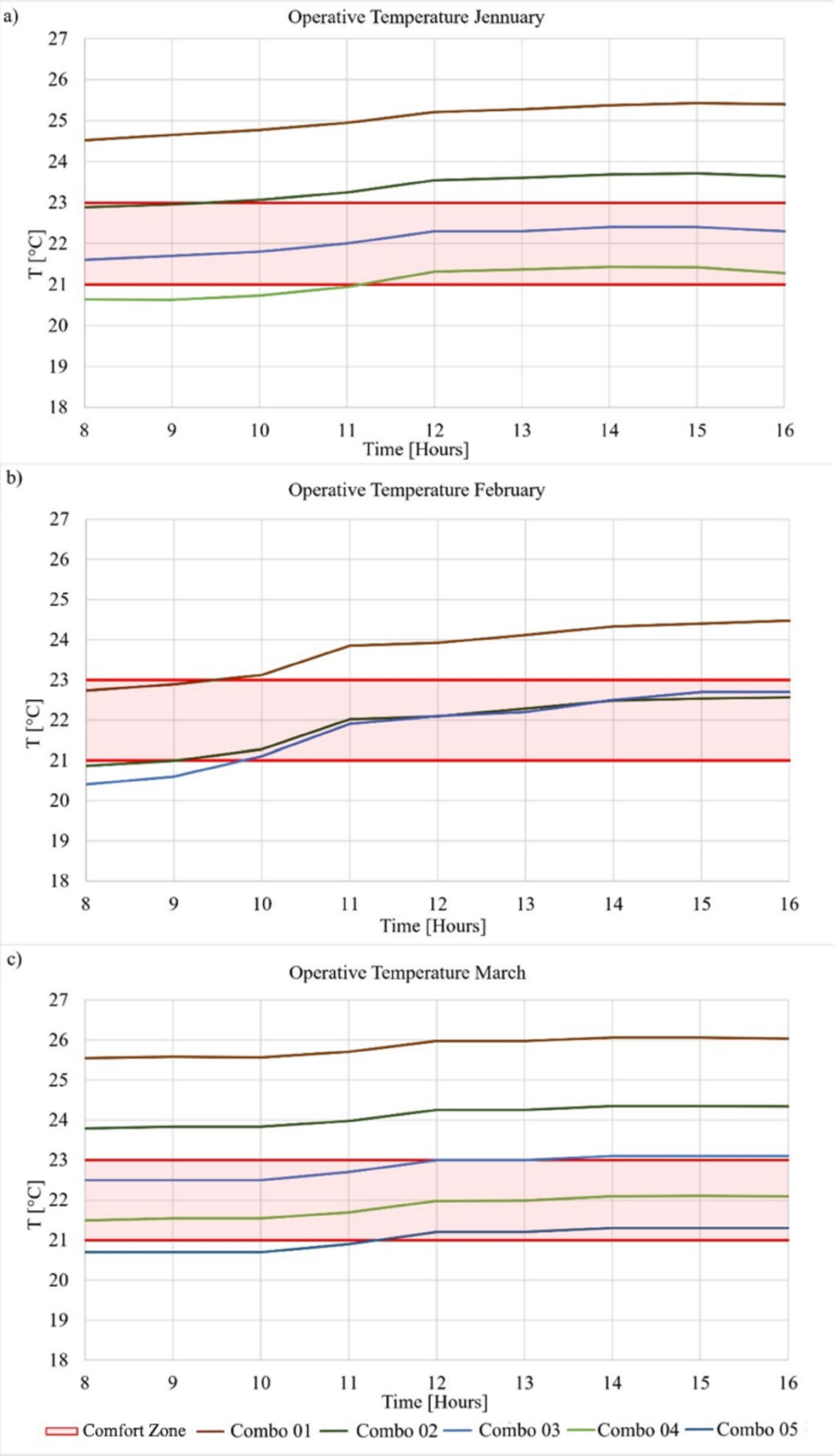
Looking at Fig. 10c for March, Combo 01 and Combo 02 still exceed the thermal comfort zone, indicating inadequate temperature control. Combo 03 successfully keeps the operative temperature within the comfort range throughout the day, similar to previous months. Combo 04 starts slightly below the comfort zone but stabilizes within the range after 10:00 a.m. Combo 05 consistently remains above the comfort zone.

In other words, Combo 03 consistently performs best in maintaining operative temperatures within the thermal comfort zone across all months, providing optimal conditions for classroom use. Combo 01, Combo 02, and Combo 05 show inadequate temperature regulation, with operative temperatures either exceeding or falling short of the comfort range. Combo 04 shows potential but requires adjustments to avoid initial temperatures below the comfort zone.

The results presented in Fig. 10 were obtained with a ventilation system without heat recovery. The assumption is precautionary, in fact, the use of a heat recuperator, by modifying the air inlet temperature within the thermal zone, increases the probability of finding the right combination of flow rate and temperature to balance the heat load.

Figure 11 reveals that in May and June, rising outside temperatures prevent maintaining classroom

Fig. 10 Operative temperature in Zone 7: **a)** January, **b)** February and **c)** March



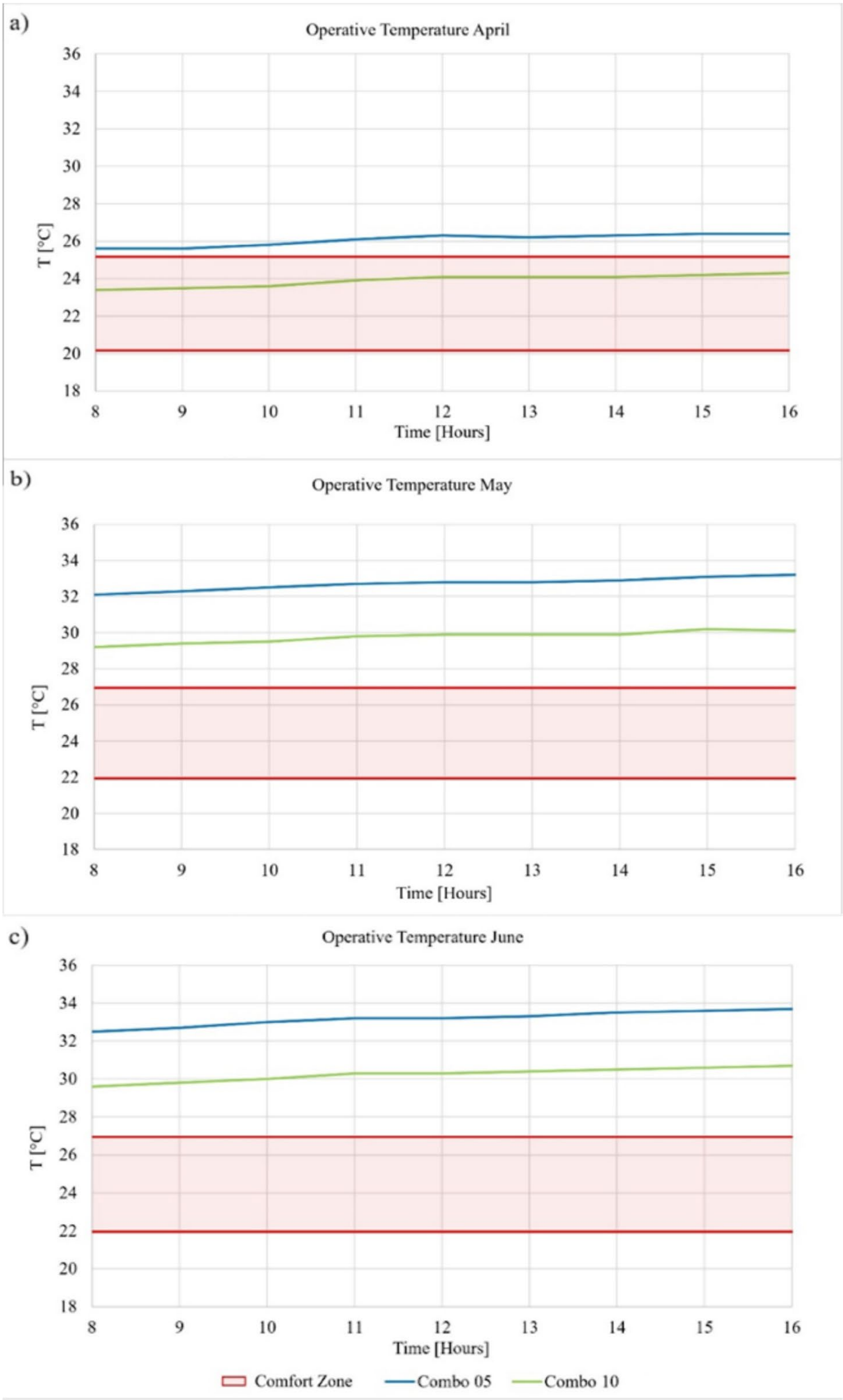


Fig. 11 Operative Temperature in Zone 7: **a)** April, **b)** May and **c)** June

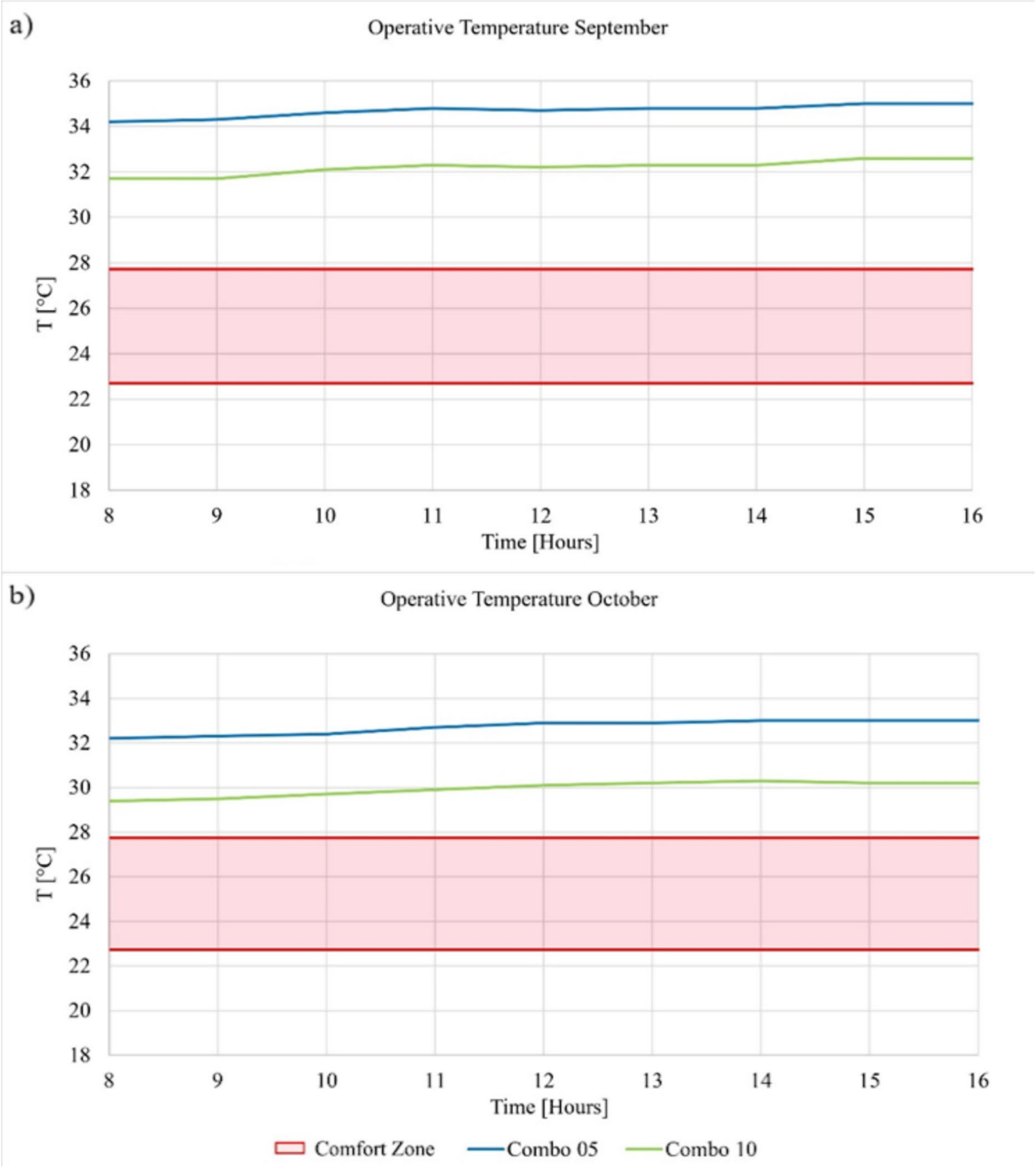


Fig. 12 Operative Temperature in Zone 7: **a)** September and **b)** October

operational temperature within the comfort zone. Only in April, with 10 air changes, does the classroom temperature fall within the comfort range.

Figure 12 shows the trend of the indoor operative temperatures in the classroom during in September and October. In these two months, it is observed that the indoor operative temperature is high and not within the thermal comfort zone for both Combo 05 and Combo 10.

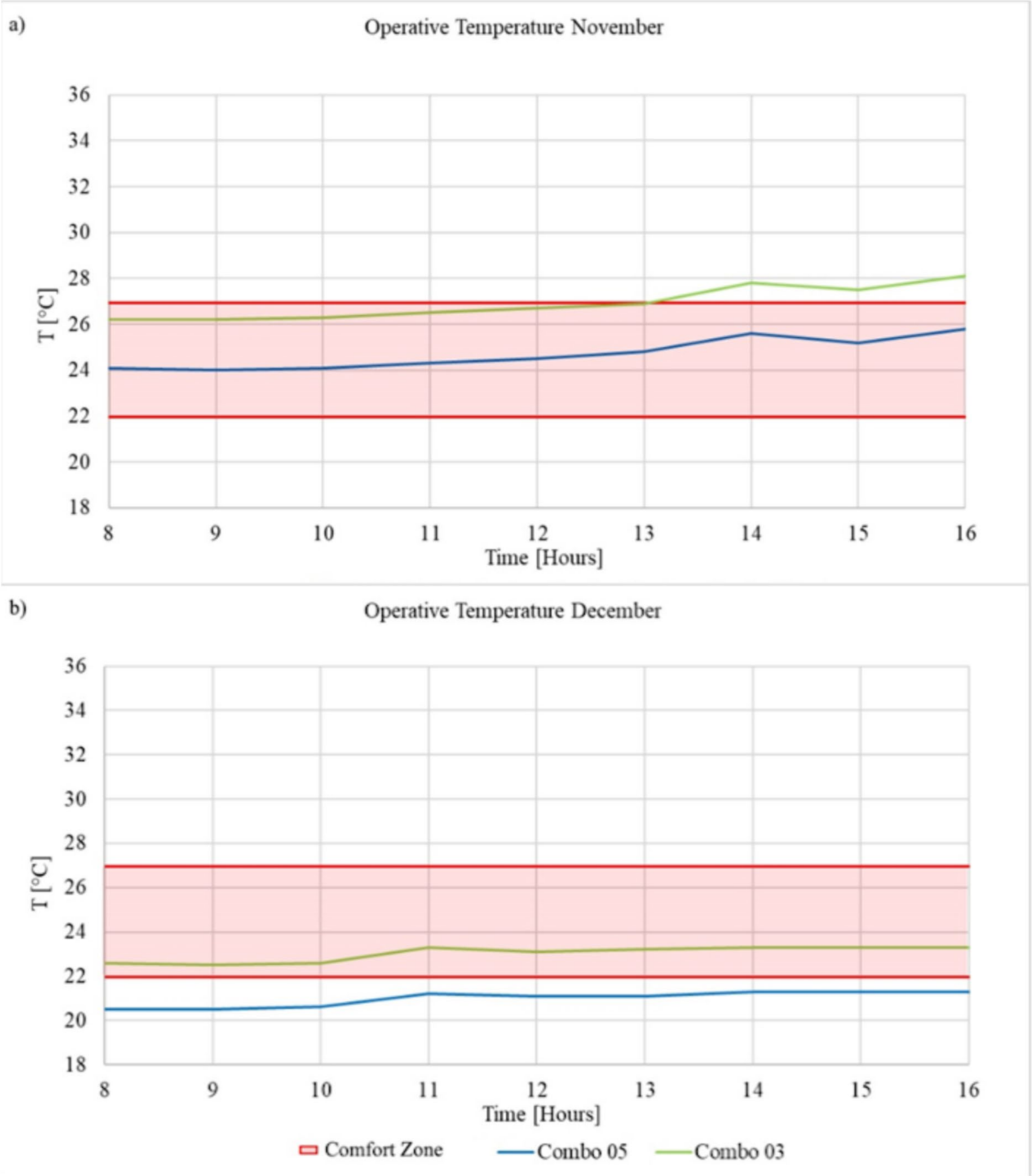


Fig. 13 Operative Temperature Zone 7: **a)** November and **b)** December

Figure 12 depicts the curves of indoor operative temperatures for the months of November and December. In November, considering Combo 03, the indoor operative temperature remains below the upper limit line of the comfort zone until 13:00. Between 13:00 and 16:00, the curve exceeds the upper limit of the comfort zone. Regarding Combo 05, it is observed that the curve of indoor operative temperature remains within the thermal comfort zone from 8:00 to 16:00. In December, Combo 05 shows a curve of indoor operative temperature below the lower limit of the thermal comfort zone from 8:00 to 16:00, while Combo 03 remains within the thermal comfort zone during the same time interval.

Yearly trends in relative humidity in a specific zone

On January 26, the coldest day of the month, it was observed that with three air changes, the specific humidity was 6.04 g/kg, while with five air changes it decreased to 5.61 g/kg, and with ten air changes it further decreased to 5.51 g/kg (Figs. 14). Analyzing the three graphs, it is clear that as the number of air changes increases, the internal specific humidity gradually decreases, approaching the external humidity more and more throughout the year. This phenomenon is entirely normal as the introduction of fresh external air, which is drier than the internal air, helps reduce the specific humidity inside the environment.

The Fig. 15 shows relative humidity trends inside the examined classroom on November 22, which was chosen as representative of several days when relative humidity values exceeded 60 percent. The data shown in the graph are for three different combinations of air exchange (Combo 03, Combo 05, and Combo 10).

The analysis shows that as the volumes of outside air supplied per hour through the ventilation system increase, the indoor relative humidity tends to rise. In particular, with Combo 10, relative humidity stabilizes at higher values, reaching about 75%.

Assessing thermal comfort in a specific zone in accordance with UNI EN 7730

For the calculation of PMV and PPD values, a "CLO" value of 1 was considered valid for indoor environments with a temperate climate (temperature below 24 °C), and a "CLO" value of 0.5 was considered valid for environments with a warm indoor climate (with a temperature above 24 °C). This parameter represents the thermal resistance provided by clothing and its ability to maintain human body thermal comfort in various environmental conditions.

In Table 2, the maximum and minimum values of PMV and PPD are reported at different times within Zone 7, considering Combo 03. These values refer to the coldest days of January, February, March, November, and December, as well as the hottest days of April, May, June, September, and October.

In Table 3, the maximum and minimum values of PMV and PPD are reported at different times within Zone 7, considering Combo 05. These values refer to the coldest days of January, February, March, November, and December, as well as the hottest days of April, May, June, September, and October.

Table 4, the maximum and minimum values of PMV and PPD are reported at different times within Zone 7, considering Combo 10. These values refer to the coldest days of January, February, March, November, and December, as well as the hottest days of April, May, June, September, and October.

Conclusions

In the Mediterranean regions many schools face common challenges in managing energy costs, striving to reduce consumption while ensuring optimal indoor air quality to enhance the performance of students and teachers. High student density and inadequate ventilation directly impact the thermal comfort of the environment, with consequent effects on learning outcomes.

The aim of this study is to explore the feasibility of foregoing heating systems in educational institutions while still achieving acceptable comfort levels during the winter months in regions with mild climates. The premise is that, in a school equipped with an efficient building envelope, the need for heating in winter can be readily met through internal heat gains, particularly those originating from occupants and devices. The concept involves managing the indoor operative temperature by adjusting the rate of ventilation. Thus, the heating requirements of a space are offset by altering the volume flow rate as the temperature of the incoming air varies. Utilizing a counterflow heat exchanger equipped with both a bypass and free-cooling capabilities provides broader operational flexibility. To maintain the indoor temperature using the ventilation rate during the winter, specific strategies are employed.

This study focused on the thermal behavior of a typical school building in the Lecce area, emphasizing the importance of proper ventilation to maintain comfortable temperatures and optimal air quality.

Fig. 14 Specific Humidity in Zone 7 (**a**) Combo 03, (**b**) Combo 05 and (**c**) Combo 10

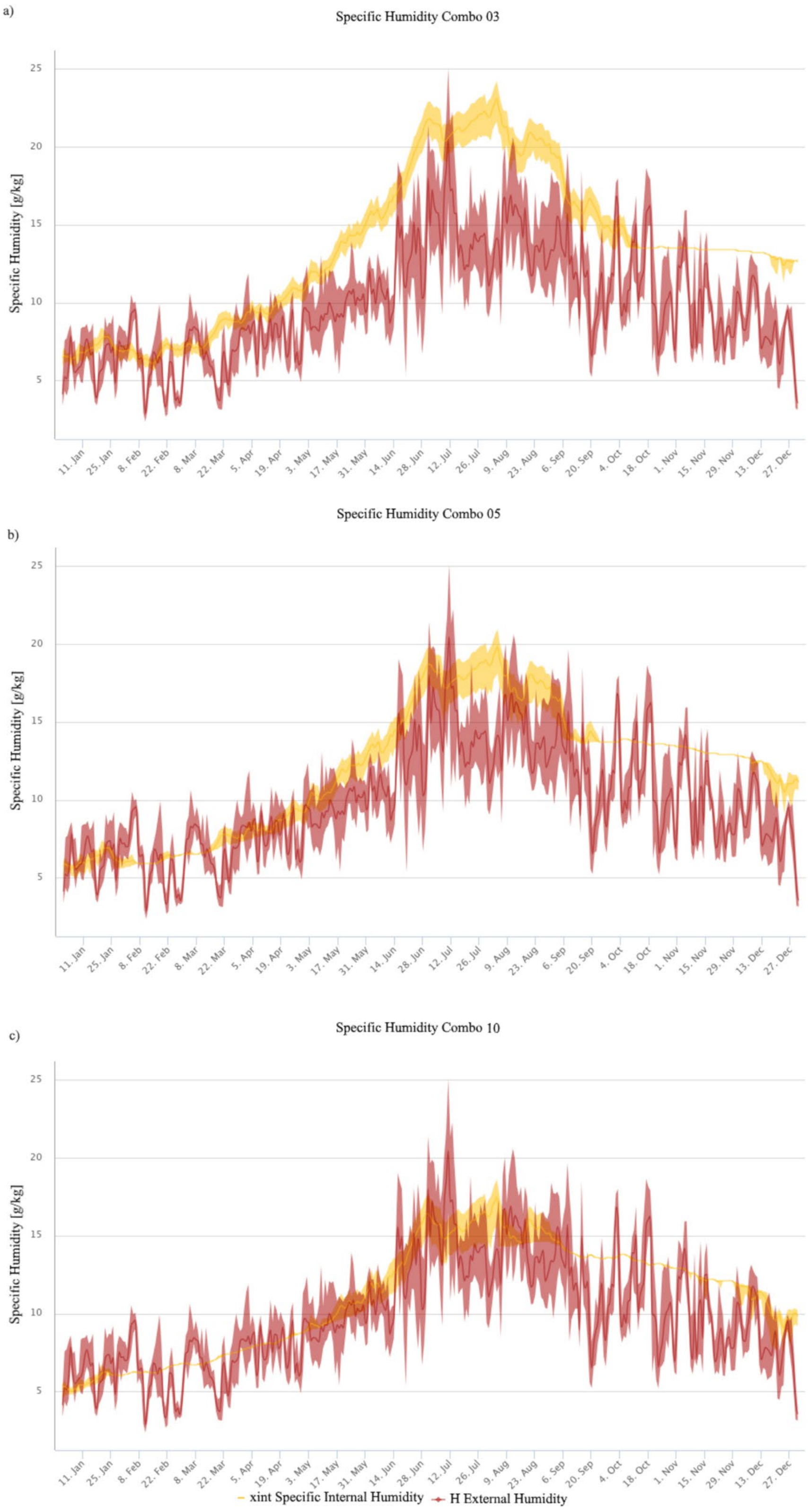


Fig. 15 Relative Humidity in Zone 7 (**a**) Combo 03, (**b**) Combo 05 and (**c**) Combo 10

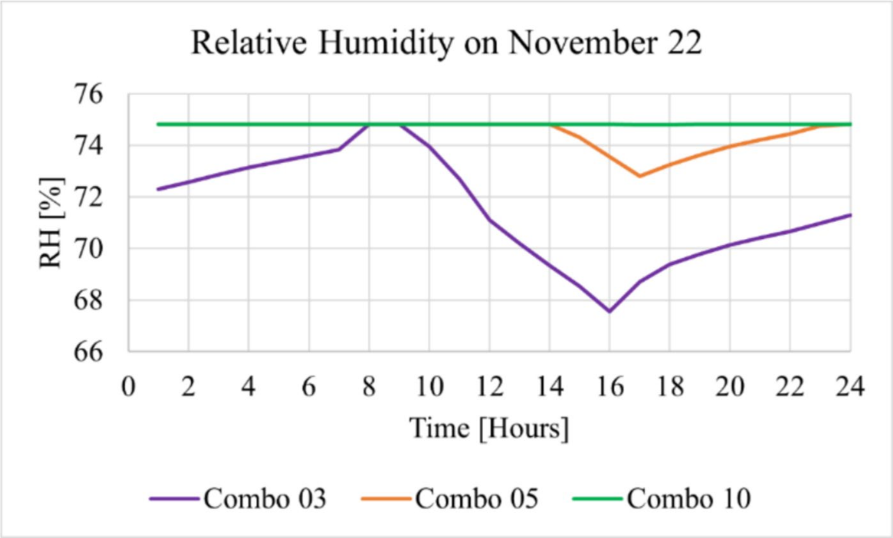


Table 2 Maximum and Minimum Values of PMV and PPD for Zone 7, Combo 03

COMBO 03	PPD	PMV	Ta [°C]	RH [%]	Text [°C]	Top [°C]	Time of Day	Day
Min	5	0.01	21.23	39.9	7.2	21.65	09:00	26 January
Max	5.31	0.12	22.24	39.9	12.3	22.35	13:00	
Min	5.28	−0.24	18.77	45.64	0.2	19.44	08:00	8 February
Max	6.17	−0.12	20.93	39.9	9	21.13	16:00	
Min	5.5	0.15	22,50	41.81	3.1	22.50	08:00	6 March
Max	6.61	0.29	23.12	40.36	11	23.08	16:00	
Min	17.22	0.76	27.32	39.9	14.1	27.31	08:00	18-apr
Max	25.77	0.99	28.13	39.91	18	28.06	16:00	
Min	98.52	2.89	34.02	39.94	21.3	34.25	08:00	31 May
Max	99.76	3.00	35.28	39.95	22.9	35.50	16:00	
Min	98.67	2.91	35.36	39.95	23.8	35.53	12:00	1 June
Max	99.46	3.00	35.92	39.96	24.4	36.09	16:00	
Min	99.91	3.00	36.22	39.97	23.2	36.21	08:00	19 September
Max	100	3.00	37.12	39.97	25.6	37.03	16:00	
Min	98.88	2.95	34.41	45.17	22	34.32	08:00	5 Ocotber
Max	99.64	3.00	35.12	43.46	24	35.29	16:00	
Min	14.22	0.66	25.7	74.81	9.8	26.2	08:00	30 November
Max	37.01	1.24	27.92	67.64	13.8	28.11	16:00	
Min	5.01	0.29	23.38	74.81	10.3	23.33	16:00	18 December
Max	6.86	0.03	22.6	74.81	2.3	22.59	08:00	

The development of this work is divided into 4 steps:

- In the first phase of the study, the evolution of the indoor operative temperature of individual classrooms within the school building was examined. This temperature varies depending on the position and exposure of each classroom, outdoor temperature, and airflow from ventilation. The study revealed that the operative temperature in Zones 1, 2, and 3, exposed to the north, fluctuates between a minimum of approximately

Table 3 Maximum and Minimum Values of PMV and PPD for Zone 7, Combo 05

COMBO 05	PPD	PMV	Ta [°C]	RH [%]	Text [°C]	Top [°C]	Time of	Day
Min	6.28	−0.29	20.23	39.9	11.9	20.62	15:00	26 January
Max	9.23	−0.47	19.01	42.95	6.5	18.83	08:00	
Min	8.9	−0.59	16.18	−55.84	0.2	17.37	08:00	8 February
Max	11.05	−0.98	18.62	47.72	9	19.12	16:00	
Min	5.14	−0,08	21.39	45.87	11.2	21.32	15:00	6 March
Max	5.98	−0.22	20.7	47.76	3.1	20.69	08:00	
Min	6.45	0.26	25.62	43.29	14.1	25.61	08:00	18-apr
Max	10.12	0.49	26.48	41.23	18	26.40	16:00	
Min	87.56	2.28	31.56	39.92	21.3	32.08	08:00	31 May
Max	94.07	2.53	32.67	39.93	22.9	33.16	16:00	
Min	89.55	2.34	32.03	39.93	22	32.53	08:00	1 June
Max	96.7	2.7	33.33	39.94	24.4	33.75	16:00	
Min	98.18	2.84	34.19	44.66	23.2	34.18	08:00	19 September
Max	99.38	3.00	35.13	42.44	25.6	35.05	16:00	
Min	89.96	2.36	31.67	52.05	22.3	31.15	08:00	5 Ocotber
Max	95.14	2.59	32.74	49.07	24.9	33.04	14:00	
Min	5.83	0.2	24.64	74.81	14.3	24.77	13:00	30 November
Max	18.66	0.8	23.85	74.81	13.4	24.48	12:00	
Min	5.01	−0.12	21.16	74.81	10.2	21.09	12:00	18 December
Max	5.32	0.03	20.48	74.81	2.5	20.47	09:00	

Table 4 Maximum and Minimum Values of PMV and PPD for Zone 7, Combo 10

COMBO 10	PPD	PMV	Ta [°C]	RH [%]	Text [°C]	Top [°C]	Time of	Day
Min	17.64	−0.77	17.61	50.93	12.3	18.27	14:00	26 January
Max	27.21	−1.03	15.73	57.34	7.2	17.2	09:00	
Min	30.95	−1.11	15.96	59.98	10.4	16.63	14:00	8 February
Max	58.3	−1.64	12.33	74.87	0.2	14.41	08:00	
Min	11.77	−0.57	19.04	54.16	11	18.99	16:00	6 March
Max	15.79	−0.72	18.3	56.6	3.1	18.29	08:00	
Min	5.3	−0.12	24.36	46.83	18	24.28	16:00	18-apr
Max	9.24	0.45	23.65	48.78	16.1	23.61	10:00	
Min	43.95	1.37	28.28	45.51	21.3	29.19	08:00	31 May
Max	59.11	1.65	29.43	42.48	23.6	30.12	15:00	
Min	50.35	1.49	28.74	44.36	22	29.602	08:00	1 June
Max	67.9	1.82	30.04	41.36	24.4	30.74	16:00	
Min	84.07	2.18	31.66	49.72	23.2	31.65	08:00	19 September
Max	91.68	2.42	32.67	47.04	25.6	32.59	16:00	
Min	53.78	1.55	28.57	59.15	22.3	29.39	08:00	5 Ocotber
Max	67.67	1.81	29.62	55.38	24.9	30.29	14:00	
Min	5	−0.01	19.83	74.81	11.7	21.22	10:00	30 November
Max	8.14	0.39	22.01	74.81	15.6	22.76	14:00	
Min	11.25	−0.55	18.7	74.82	10,3	18.65	16:00	18 December
Max	17.13	−0.76	17.75	74.83	2.5	17.74	09:00	

13 °C with Combo 10 and a maximum over 40 °C with Combo 01. This situation is more critical in Zones 7, 8, and 9, exposed to the south of the building, where the minimum operative temperature is around 13.6 °C with Combo 10 and reaches a maximum of over 40.0 °C with Combo 01.

- In the second phase of the study, it emerged that during the winter months, particularly in January, February, and April, it is possible to maintain an indoor operative temperature suitable for thermal comfort without the need to activate the air conditioning system, simply by managing the ventilation of the environment. However, this phase also highlighted the difficulties of the building in maintaining an indoor operative temperature suitable for adaptive thermal comfort during transitional periods, such as spring and autumn, and during the warmer months.
- In the third phase of the study, the focus was on evaluating the specific humidity of Zone 7, highlighting how an increase in air exchange leads to a greater adaptation of specific humidity to the external environment.
- In the final stage of the work, thermal comfort was evaluated based on PMV and PPD parameters, showing the percentage of dissatisfaction in Zone 7 by varying ventilation.

The results of this study highlight a crucial challenge for the education sector: the impact of ongoing climate change on school environments. With rising global temperatures and increasing extreme weather events, school buildings are exposed to growing risks, ranging from excessive summer heat to difficulties in maintaining comfortable temperatures during winter. This situation not only compromises the well-being of students and staff but also affects academic performance and learning conditions.

Addressing this challenge requires a holistic approach that goes beyond simple energy saving. Technological solutions must be designed considering not only energy efficiency but also the overall environmental impact, adopting low-emission technologies and eco-friendly materials. Additionally, it is essential to integrate advanced energy management systems that allow for real-time monitoring and optimization of energy consumption, adapting it to environmental conditions and actual space usage.

At the same time, it is crucial to ensure a comfortable and healthy indoor environment to facilitate optimal learning. This includes not only temperature regulation but also management of humidity, air quality, and brightness, through the adoption of efficient ventilation systems, high-quality air filters, and adequate natural and artificial lighting.

Furthermore, actively involving key stakeholders, including school administrations, local institutions, communities, and students themselves, in the design and implementation of these solutions is important. Environmental education and awareness-raising on sustainable practices can help create a culture of environmental respect within schools and their communities, promoting responsible behavior and awareness of environmental issues.

Ultimately, addressing the impact of climate change on school buildings is not just a matter of energy efficiency but also of ensuring a healthy, safe, and stimulating environment for today's students and future generations.

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Declarations

Conflict of interest The authors declare that they have no conflict of interestThe authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from cristina.baglivo@unisalento.it.

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