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Original
Mechanical Ventilation and Indoor Environmental Quality: Experimental Comparison Between Two Decentralised Systems in School Classrooms / Summa, S., Cippitelli, M., Di Perna, C., Stazi, F.. - (2025). (12th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering), Colloqui.AT.e 2025 Trento 11 - 14 June 2025) [10.1007/978-3-032-06978-8_40].

Availability:
This version is available at: 11566/349492 since: 2025-11-01T23:00:13Z

Publisher:
Springer

Published
DOI:10.1007/978-3-032-06978-8_40

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07 November 2026

Mechanical ventilation and Indoor Environmental Quality: Experimental comparison between two decentralised systems in school classrooms

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Abstract. This paper presents a comparison between two types of controlled mechanical ventilation (CMV) decentralised systems in school classrooms: one with an internal unit within the classroom (I), and one with ducts located in the ceiling (C). The main results show that, in terms of indoor air quality evaluation, CO_2 levels in classrooms are influenced by both the opening or closing of doors and windows, as well as by the mechanical ventilation system. Only the classroom with the ceiling-hosted system (C) maintains acceptable CO_2 levels solely through the system's contribution, without the need to open the windows. The three-dimensional comfort mapping demonstrates a uniform microclimatic condition in the C classroom, while the I classroom records localised discomfort.

Keywords: Three-dimensional comfort mapping, Perceived comfort, Controlled mechanical ventilation systems, Thermal Manikin, User behaviour.

1 Introduction

Most people spend between 60% and 90% of their lives indoors (in their homes, offices, schools, etc.), where the air quality can be up to five times more polluted than outdoors [1]. The World Health Organization (WHO) has identified a strong correlation between poor indoor air quality (IAQ) and a range of health issues, including respiratory diseases, asthma, allergies, cardiovascular problems, and neurological disorders [1–5]. Additionally, numerous studies have highlighted that the effects of poor IAQ are particularly pronounced in school-aged children. Therefore, monitoring and improving IAQ levels in classrooms is of utmost importance, as children spend up to 1075 hours per year in these environments [6]. In addition to negatively impacting health, poor IAQ also limits cognitive abilities and concentration, which are crucial for learning [7, 8]. The most widely used indicator of IAQ in classrooms is the concentration of carbon dioxide (CO_2) [9, 10] since it is directly correlated with the high crowding index typical of these environments [11]. The presence of many occupants in school environments is a key factor, resulting in an average CO_2 concentration during occupancy that is 150%

higher than during the unoccupied period [12]. Most studies in school classrooms report CO_2 values exceeding the limits set by standards [13–15]. One study shows average CO_2 values exceeding 1000 ppm in 70% of the 10 classrooms investigated [16]. Other authors highlight that in 70% of the 75 classrooms in the analysed sample, the threshold limit was exceeded for more than half of the time the classrooms were occupied [17].

In buildings with natural ventilation, the improvement of air quality depends on all the factors that influence greater occupant interaction with window openings and on the effectiveness of air exchange, which is related to the characteristics of the building and the room. Natural ventilation is considered a sustainable system as it significantly reduces energy consumption by utilising outdoor air to refresh the indoor environment. However, in winter season, opening windows causes energy loss because natural ventilation refreshes the environment. Moreover, the air fed into the environment is not subjected to any filtration process for external pollutants and contributes to noise pollution (caused by external noise), except in the case of adopting innovative solutions specifically designed for this purpose [18]. It has been demonstrated that outdoor temperature influences user interaction with windows [19], thereby affecting indoor air quality. In the literature, one study showed that despite poor air quality, there is no interaction with windows when outdoor temperatures are below 15°C [20]. Furthermore, it has been shown that the influence of temperature on window opening and closing varies depending on indoor pollution levels [21]. For instance, numerous studies have agreed that under poor IAQ conditions, occupants are disposed to accept lower air temperatures [13, 14, 22]. Among the building factors that positively influence the effectiveness of natural ventilation include: the location, shape, type, orientation, and size of openings, as well as the room geometry [23]. Additionally, the relative position between windows and doors, and the airflow path (unidirectional, cross-ventilation, atriums, and chimneys) also affect the ventilation efficacy [12].

Controlled ventilation could be a solution to the above-mentioned issues. Although it has been demonstrated that mechanical ventilation ensures better thermal comfort in all seasons (especially during winter) and superior air quality due to higher average air exchange rates compared to classrooms with natural ventilation [19], this system is still rarely implemented today. Classrooms with mechanical ventilation, regardless of classroom characteristics, record lower CO_2 levels compared to those with natural ventilation [17, 19], with the frequency of exceeding 1000 ppm reduced by half (29% and 57% of the time, respectively, during school hours). Some studies [19, 24–26] suggest the greater efficiency of hybrid systems. One study, in fact, reports CO_2 concentrations in mechanically ventilated classrooms that are 8% lower than those with natural ventilation, and even lower CO_2 levels for classrooms with hybrid ventilation (with a further 8% reduction compared to those with only mechanical ventilation) [27]. There is a lack of studies on the comparative analysis of different mechanical ventilation systems in school environments.

Regarding the methods for studying indoor environmental quality in school classrooms, the literature suggests subjective methods, such as questionnaires, and objective methods using sensors. Most studies use sensors at a single point in the classroom to analyse IAQ and thermal comfort [16, 17, 27–31]. Studies on three-dimensional comfort mapping, aimed at highlighting differences based on position relative to the

window, are much rarer [32]. Interesting works in this field have mapped thermal comfort and air quality in academic spaces with natural ventilation to analyse local variations in temperature, air velocity [33], and CO_2 [34]. The use of advanced sensors such as thermal manikin, typically employed in test rooms [35], has rare applications in real-world school environments. Among real-world applications, one study used a thermal manikin to investigate the cooling effect on the manikin's body surface produced by ceiling fan systems; however, the study does not pertain to a school environment [36].

Despite the numerous studies on comfort and IAQ in school environments, the literature has highlighted the following open issues: (i) few studies are comparing different controlled mechanical ventilation (CMV) systems in school classrooms; (ii) data collection is limited to single points within the environments, highlighting the need for three-dimensional comfort mapping; (iii) studies in classrooms through advanced sensors such as the thermal manikin are limited.

The present study aims to contribute to the ongoing debate by investigating the effectiveness of two decentralised mechanical ventilation systems: one with an internal unit within the classroom (I), and the other with the unit and ducts located in the ceiling void (C). Two classrooms representative of the school building stock in the Marche Region were selected. Three-dimensional maps of the main microclimatic and comfort parameters were elaborated, and the perception of the homogeneity of the indoor environment was analysed using a thermal manikin.

2 Methods

2.1 Case studies

The experimentation was conducted in two school classrooms, one in Falconara Marittima (classroom I) and the other in Recanati (classroom C), as shown in Figure 1. The average monthly minimum external temperature is 2°C, while the maximum is 28°C in both locations [37] which fall within climate zone D according to Presidential Decree 412/1993 [38]. The selection of the case studies was made following a typological analysis of the Marche Region's school heritage, which identified representative archetypes [39]. The two classrooms are both characterised by a square shape, located on the first floor, a heating system with radiators and a decentralised mechanical ventilation system with three-speed settings, entering fresh air from outside. The decentralised system, as opposed to the centralised system with only one large ventilation machine serving several rooms via ducts, is a system in which each room has its own ventilation machine sized with respect to the volume of air to be exchanged according to the national standard DM 18/12/1975 [40].

In the type I system (school in Falconara Marittima), the air change rate is 750 m^3/h, and there is a mechanical ventilation unit placed inside the classroom on which there are two grilles, a front supply one and a lower extraction one. The supply of clean air and the extraction of stale air therefore takes place from a single point in the room.

In the C system (school in Recanati), the air change rate is 500 m^3/h, and there is a ventilation unit placed inside the false ceiling from which two pipes for the supply air and two for the extract air depart. These pipes arrive at the respective helicoidal

diffusers also positioned in the false ceiling, which allow the room to be cleaned by inserting and withdrawing air from 4 different points. All the parameters of the two classrooms are shown in Table 1.

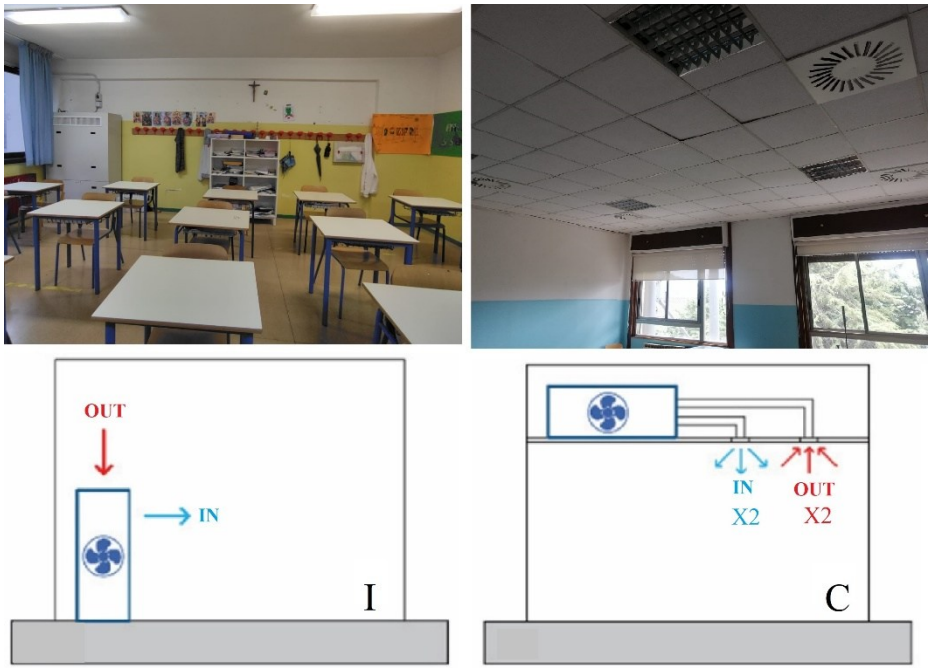

Fig. 1. On the left, the classroom with an internal unit system (I); on the right, the classroom with system hosted in the ceiling void (C)

Mechanical ventilation system	I	C
Location	Falconara Marittima	Recanati
Type of school	Lower secondary school	Primary school
School schedule	8:00 - 13:45	8:20 - 16:20
Number of students	22+1 teacher	24+1 teacher
Classroom area [m^2]	49.00 (7.15 m*6.85 m)	44.20 (6.40 m*6.90 m)
Classroom height [m]	3.60	3.00
Classroom volume [m^3]	176	131
Window area [m^2] (%)	9.40 m^2 (38%)	5.60 m^2 (26%)
Window orientation	N-E	S-E
Ventilation type	Single side	Cross ventilation

Table 1. General data of the two classrooms

2.2 Measurement instruments

In the two classrooms an experimental campaign was carried out: from 15 to 21 March 2023, for classroom I, and from 8 to 14 May 2024, for classroom C. To characterise the two case studies in terms of thermal comfort and indoor air quality, CO_2 levels and air temperature were recorded at one point in the room (HOBO symbol in Figure

2). Air temperature was measured according to the EN ISO 7726:2002 standard [41], while CO_2 was measured according to the EN ISO 16000-26:2012 standard [42].

Additionally, a COMFORT SENSE microclimatic station from DANTEC Dynamics was used for three-dimensional mapping, measuring comfort parameters at 13 points in the classrooms. The parameters were acquired at three heights: 10 cm, 60 cm, and 110 cm from the floor, corresponding to the ankles, hips, and head in the sitting position of the user according to ISO 7730 standards [43] (Dantec in Figure 2). The measurements were taken with the ventilation system switched on, and the windows and door closed. The parameters acquired included: air velocity, air temperature, predicted mean vote (PMV), and the predicted percentage of dissatisfied people (PPD). The Tecplot 360 software allowed the three-dimensional and two-dimensional mapping of the collected data.

Through contact sensors installed on the top frame of the door and windows, it was possible to determine the state (open or closed) of windows and door (WD and DR in Figure 2).

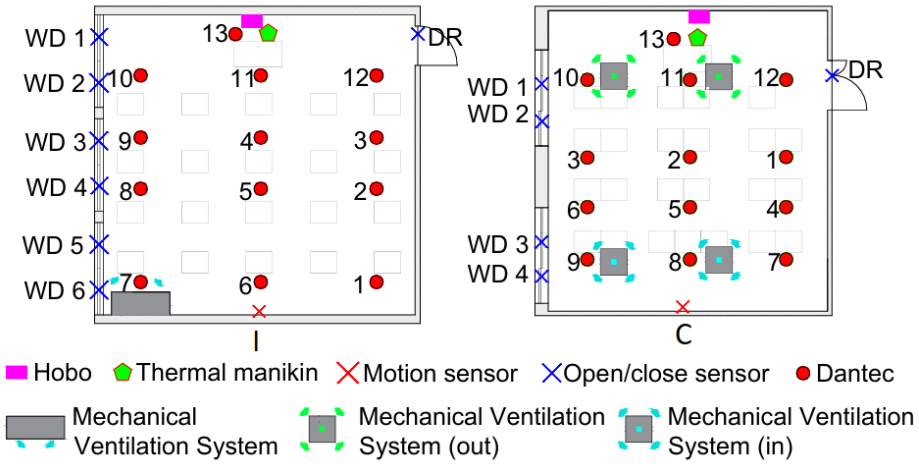

Fig. 2. Floor plan and monitoring project of classrooms in the schools of Falconara Marittima (I) and Recanati (C)

The measuring instruments used for the acquisition of the parameters are listed in Table 2. The data acquisition interval was 5 minutes.

Sensors	Model	Measure	Range	Accuracy
Data logger	HOBO MX1102A	Air Temp.	0°C ÷ + 50°C	± 0.21°C
Data logger	HOBO MX1102A	CO_2	0 ÷ 5000 ppm	± 50 ppm
Thermo Anemometer	Dantec Dynamics	Indoor Air Temp.*	-20°C ÷ 70°C	± 0,2 K
Thermo Anemometer	Dantec Dynamics	Indoor Air Vel.*	0,05 ÷ 10	± 5%

-	Dantec Dynamics	PMV/PPD	-	-
Thermal manikin	PT TEKIK	Equivalent Temp.	15°C-45°C	± 0,5%
Thermal manikin	PT TEKIK	PMV	-	-
Thermal manikin	PT TEKIK	PPD	-	-

Table 2. Measuring instruments. *Values recorded at 10-60-110 cm

Finally, the use of a thermal manikin (Figure 3) with 27 measurement zones enabled the replication of the comfort perception of an adult subject with a height of 175 cm. Measurements were taken in a seated condition simulating the teacher's position (position reported in Figure 2), during the summer period, with the ventilation system active and the door closed, in two test configurations of the classroom: windows closed (CW) and window WD1 open (OW).

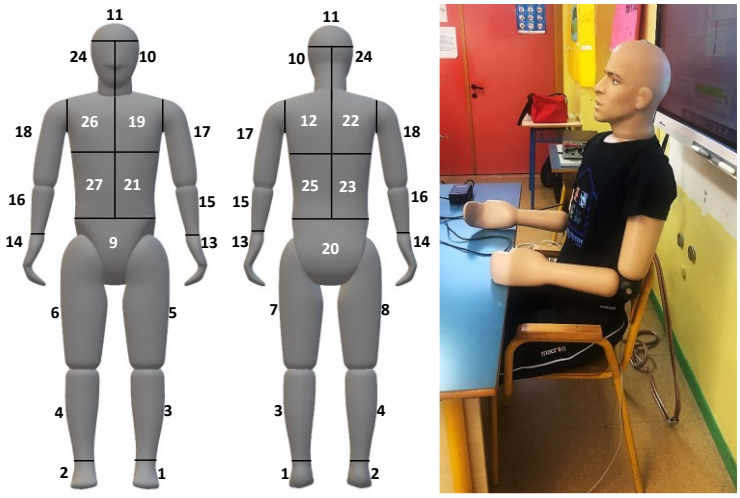

Fig. 3. Front and back views of the thermal manikin with the identification of the 27 thermal zones

The limit values for air temperature and CO_2 during the winter season for school classrooms are 20 ± 2°C and 1350 ppm, as specified in the Italian regulation DM 18/12/75 [40] and the technical standard EN 16798-1:2019 [44], respectively.

3 Results

3.1 Microclimatic analysis

The air velocity map of the classroom with a type I system is shown in Figure 4 on the left. The data demonstrates that all points record a velocity of 0.05 m/s, except for positions 8, 9, and 10 (in front of the air supply diffuser), where the recorded velocities were 0.60 m/s, 0.15 m/s, and 0.10 m/s, respectively. The corresponding section A-A

shows that the maximum velocity is recorded at point 8, 110 cm above the ground, representing a localised discomfort zone.

The air velocity map of the classroom with system C is reported in Figure 4 on the right. It shows that the maximum air velocity (0.038 m/s) is recorded at point 10, corresponding to the air return grille. In other points, the recorded velocities are homogeneous, ranging from 0.024 to 0.029 m/s. The corresponding section B-B highlights the maximum velocity at point 10, at 110 cm from the ground, while at points 9, 6, and 3, the highest velocities are recorded closer to the ground, between 10 and 60 cm. The supply grille introduces air that touches the area closest to the floor in the central part of the room before rising toward the return grille.

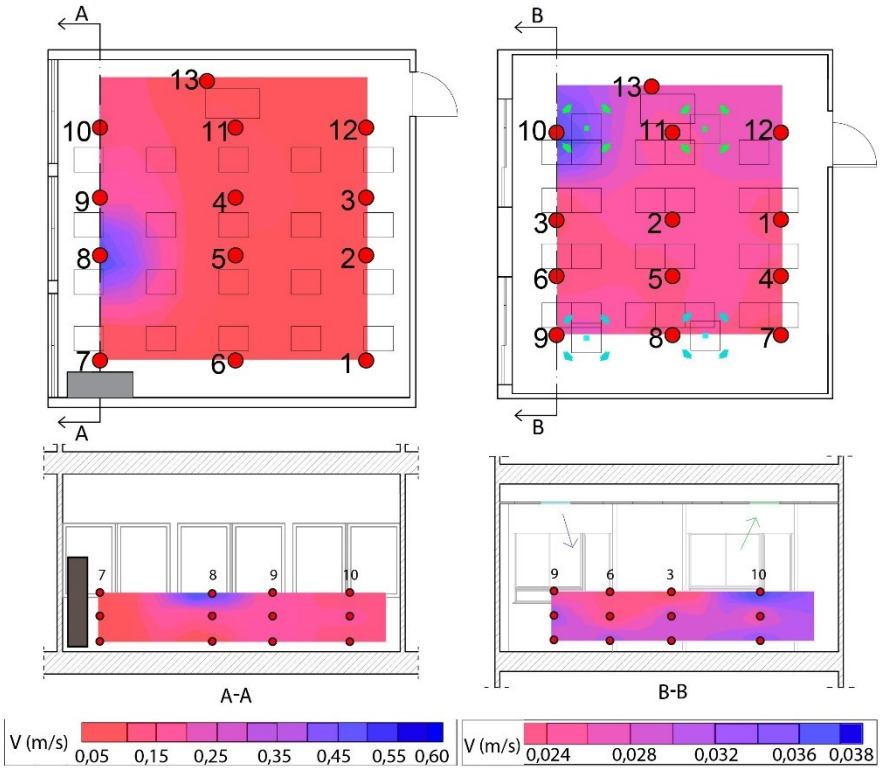

Fig. 4. The air velocity maps (at 110 cm) along with the transversal sections (10 cm, 60 cm and 110 cm) are shown on the left for class I and on the right for class C

The thermal map in Figure 5 on the left is related to classroom I. The figure shows higher air temperatures at points 2 and 5 (center of the room), while the temperature decreases at the outer points, primarily at points 1 and 6. The temperature reduction at point 1 is due to its proximity to the door that divides the classroom from the corridor, while at point 6 it is caused by the higher air velocity from the system, as highlighted in the air velocity map in Figure 4 on the left. From section A-A, it can be observed

that the air temperature is homogeneous at all heights at point 2, while it is lower at points 1 and 3, which are closer to the window and the partition wall, respectively. Figure 5 on the right shows the air temperatures recorded in classroom C. The highest temperature is recorded at point 3 (20.6°C), while at the other points, the temperature remains constant and is approximately 0.5°C lower. From section B-B, it can be observed that the air temperature is higher at 110 cm in all positions and decreases as it moves lower. The temperature stratification is in line with the B-B section in Figure 4.

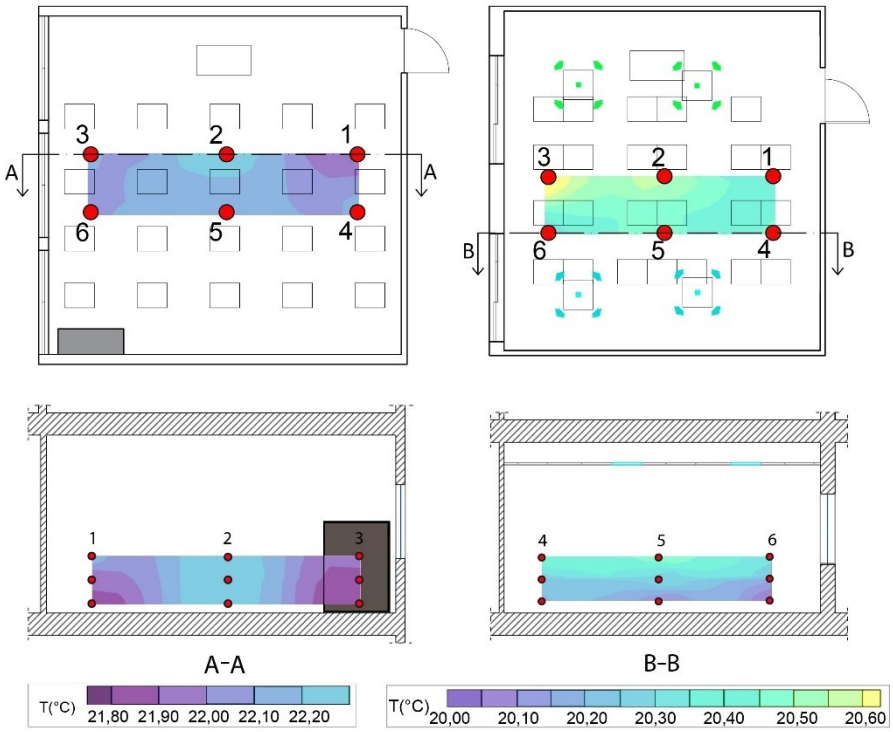

Fig.5. The Air temperature maps (at 110 cm) along with the transversal sections (10 cm, 60 cm and 110 cm), are shown on the left for class I and on the right for class C

Figure 6 illustrates the PMV recorded within classroom I on the left. At the 6 measurement points, the PMV ranges from -1.45 to -1.05, indicating a comfort perception between slightly cool and cold. The area of greatest discomfort is at point 3, where the PPD reaches a value of 50%, meaning that half of the users are in a state of thermal discomfort. The central points (2 and 5), however, show the least discomfort, with PPD values of 28%-29%.

In classroom C (Figure 6 on the right), the PMV ranges from -0.43 to -0.51, indicating that users perceive a state of full comfort. Consequently, the PPD values are very

low. Point 6 records the lowest PMV of -0.51, with a dissatisfaction rate of 11%. All other points show a PMV of -0.43, with only 9% of users reporting dissatisfaction.

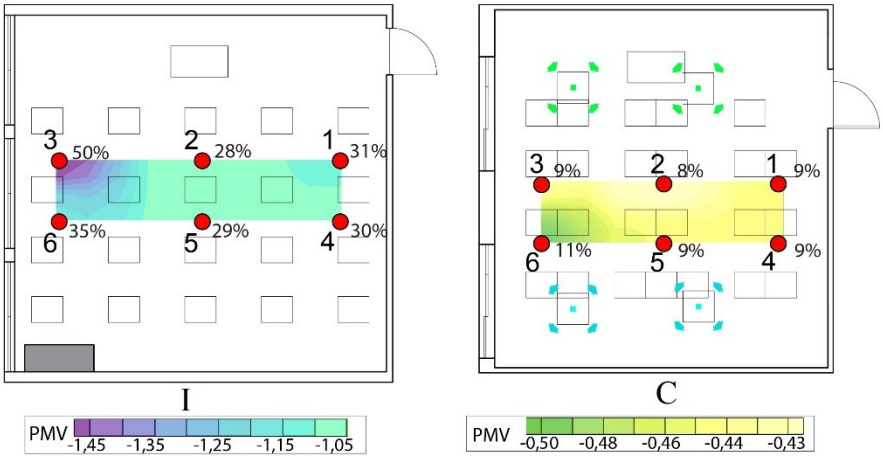

Fig. 6. PMV and PPD maps, class I and class C

3.2 Indoor Air Quality and user behaviour

To assess air quality in the two classrooms, an analysis of CO_2 trends in relation to user behaviour (opening and closing of windows and doors) was conducted. The two days with the highest CO_2 concentration values were analysed: classroom I, on 20th March 2023, with a maximum value of 1467 ppm, and classroom C, on 10th May 2024, with a maximum value of 1239 ppm.

By placing opening and closing sensors on all window sashes and on the door of classrooms I and C, it was possible to determine which windows were most frequently used by the occupants, evaluating the percentage of time the windows were open. This was calculated as the ratio of the number of times the window was recorded as open compared to the total hours of classroom occupancy (Table 3). In classroom I, the window closest to the teacher's desk (W1) was found to be the most frequently used, along with the window at the far end of the room (WD6). This pattern was consistent for all days during the monitoring period; furthermore, two of the six window sashes considered were never opened (WD2 and WD4). In classroom C, since the monitoring was conducted in May, there was a very high percentage of window and door openings. The most frequently used windows were 2 and 4, respectively the one closest to the teacher and the one at the far end of the classroom, confirming the same behavior observed in classroom I.

I	DR	WD1	WD3	WD5	WD6	**C**	DR	WD2	WD3	WD4
15/03	12%	7%	36%	0%	0%	**08/05**	59%	89%	0%	66%
16/03	37%	34%	49%	0%	32%	**09/05**	38%	100%	0%	100%
17/03	19%	5%	0%	0%	0%	**10/05**	22%	0%	25%	25%
20/03	15%	16%	0%	26%	26%	**13/05**	95%	100%	0%	67%
21/03	18%	32%	0%	0%	12%	**14/05**	64%	94%	0%	94%

Table. 3. The percentage of window and door opening time in classroom I between 8:00 AM and 2:00 PM, and in classroom C between 8:20 AM and 12:20 PM and between 2:00 PM and 4:00 PM.

The graphs in Figures 7 and 8 show the trends of indoor air temperature and CO_2 levels in relation to window openings (indicated by the upper bars) and door openings (grey area in the graphs) for classrooms I and C, respectively.

Regarding classroom I (Figure 7), the effects of mechanical ventilation are evident in the initial phase with windows closed, where the recorded CO_2 levels are solely regulated by the ventilation system. It is observed that CO_2 rises from 8:20 AM until approximately 9:25 AM, then remains constant at an average value of 1375 ppm until 12:00 PM, when the door is opened simultaneously with windows 1 and 6. These changes cause a rapid decrease in CO_2 from 1320 ppm to 931 ppm within 10 minutes. The door closing at 12:10 PM, despite the opening of windows 5 and 6, results in a CO_2 increase to 1286 ppm, indicating that effective ventilation only activates in a cross-ventilation mode, with the simultaneous opening of the door and windows. Subsequently, from 12:40 PM to 12:55 PM, a further CO2 reduction is observed, dropping to 750 ppm due to windows 5 and 6 and the door being open. CO_2 remains at an average value of 780 ppm until 13:45 PM, the students' exit time, and then gradually decreases to levels associated with unoccupied conditions (around 550 ppm).

The temperature trend is also strongly influenced by cross-ventilation: an increasing trend is observed until 11:35 AM, followed by a decrease upon the opening of the door and windows, reversing the trend.

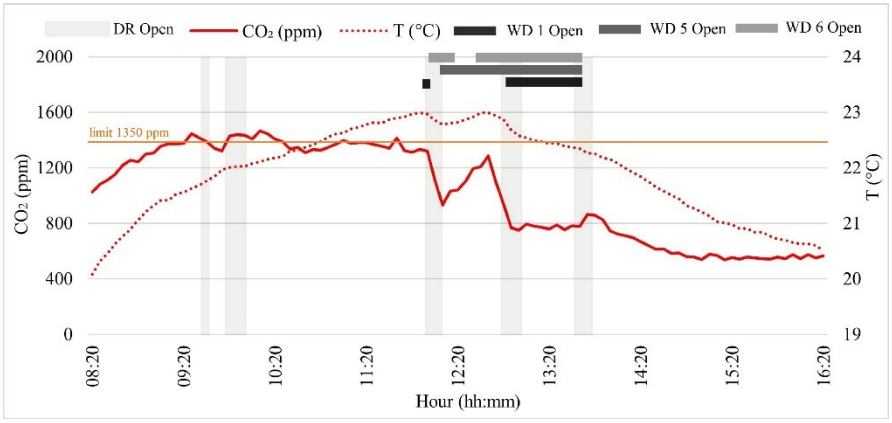

Fig. 7. Trend of CO_2 and air temperature with the opening of doors and windows in Classroom I on March 20, 2023

For classroom C (Figure 8), a similar trend to classroom I can be observed. The windows remain closed in the morning and are only opened from the early afternoon (14:30), allowing the effectiveness of the mechanical ventilation system to be assessed. Thanks to the system, CO_2 levels do not exceed 1230 ppm, well below the limit set by the regulations of 1350 ppm (EN 16798–1:2019[44]). As observed in classroom I, the opening of only one control system (either the door or windows) does not contribute to the reduction of CO_2 levels or indoor temperatures.

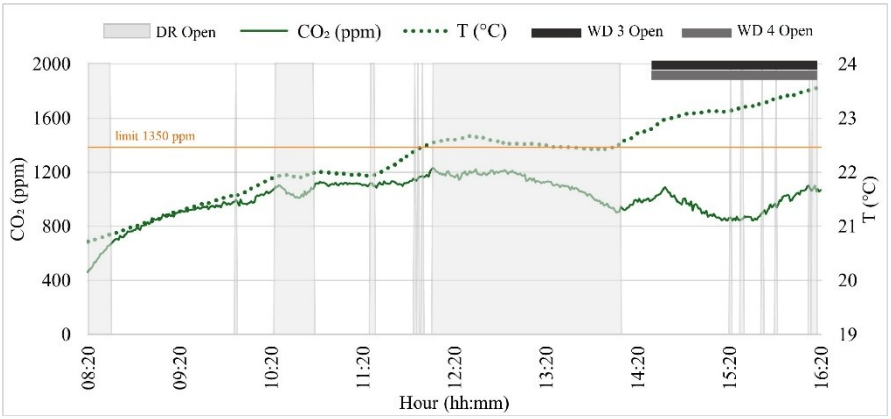

Fig. 8. Trend of CO_2 and air temperature with the opening of doors and windows in Classroom C on May 10, 2024

In general, the CO_2 concentration in the two classrooms is influenced by both the opening of the windows and the door, as well as the presence of the mechanical ventilation system, which helps maintain levels lower than those that would be achieved without it [19, 24–26]. In classroom I, a combination of these two strategies is necessary to achieve acceptable IAQ levels, as shown in the graph in Figure 7, where the CO_2

limit recommended by the regulations for school buildings (1350 ppm) was exceeded, although not significantly (by 25 ppm). The C system proved particularly effective, managing to maintain an acceptable level of air quality without relying on natural ventilation. Another aspect revealed by the analysis is that, for both classrooms, the windows are opened once the temperature exceeds 23°C. This data could be useful for designers of hybrid ventilation systems.

3.3 Comfort analysis using a thermal manikin

The thermal manikin allowed for the evaluation of comfort parameters perceived by an average adult male during the summer season. In the same position, air temperature and air velocity were recorded for each test condition: with all the windows closed (CW) and with one window open (OW) (Table 4).

In classroom I, when the windows are closed, the air velocity is approximately 0.030 m/s at all three heights. When the window is open, an increase in air velocity is recorded at all three heights, with the greatest increase at 110 cm. Regarding air temperature, a decrease of over 0.50°C is recorded at 110 cm thanks to the particularly favourable position of the window relative to the teacher's desk. Additionally, vertical temperature stratification (about 1°C) is present both with the window open (due to natural ventilation) and closed (due to mechanical ventilation).

In classroom C, the air velocity recorded at the three heights is around 0.026 m/s with the windows closed. When the window is open, there is an increase in air velocity, reaching values around 0.123 m/s at all three heights. Regarding air temperature, there is little difference (about 0.18°C) between the conditions with the windows closed and with the windows open. With the windows closed, the system causes less temperature stratification compared to system I (a gradient of about 0.5°C between head and feet).

Class	Height	T,a,_CW	W,a_CW	T,a_OW	W,a_OW
I	10 cm	27,41	0,027	27,07	0,054
	60 cm	28,07	0,030	27,58	0,061
	110 cm	28,52	0,030	27,98	0,102
C	10 cm	27,51	0,026	27,55	0,122
	60 cm	27,90	0,026	27,73	0,124
	110 cm	28,09	0,027	27,91	0,123

Table 4. Air temperature and velocity in classrooms I and C in the two test configurations (OW and CW) measured with the Comfort Sense system by Dantec Dynamics

In Figure 9, a graph is presented showing PMV values for the two classrooms. Both with windows closed and with one window open, a sense of discomfort is noted due to high temperatures. The average PMV values with windows closed are higher than those in the open window condition, with a 20% increase in classroom C and a 10% increase in classroom I. This implies that with windows open and the system active, better comfort can be achieved in the classroom, as also observed in the air quality analysis.

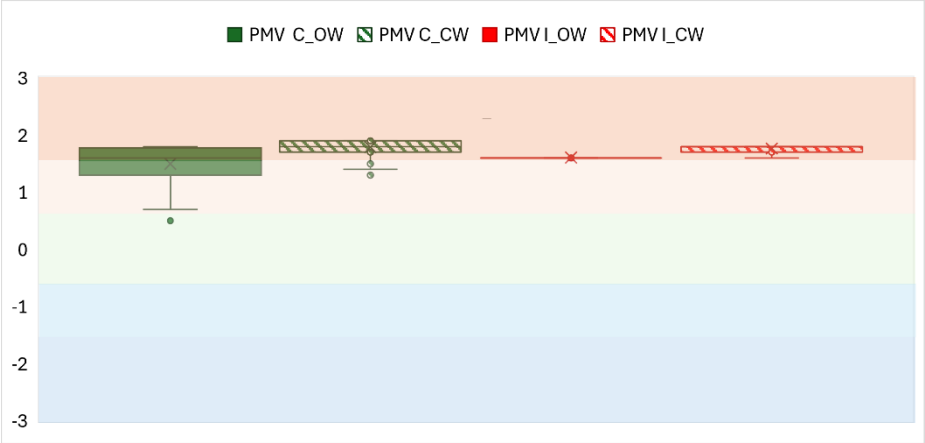

Fig. 9. PMV recorded by the thermal manikin in classrooms I and C in the two test configurations (OW and CW)

Figure 10 shows the trends of the average equivalent temperatures recorded in each zone of the manikin for both test conditions in the two classrooms. In both classrooms, higher average equivalent temperatures are recorded for all considered zones (10 cm, 60 cm, and 110 cm) in the windows-closed configuration. With the opening of a window, the average equivalent temperature in the central part of the manikin (60 cm) decreases by an average of 0.92°C in classroom C and 0.42°C in classroom I. The largest difference is observed in classroom C, particularly in the body areas in contact with the chair, with a difference between Teq CW and Teq OW of over 1°C. This is due to the increase in air velocity recorded with the windows open in classroom C (see Table 4).

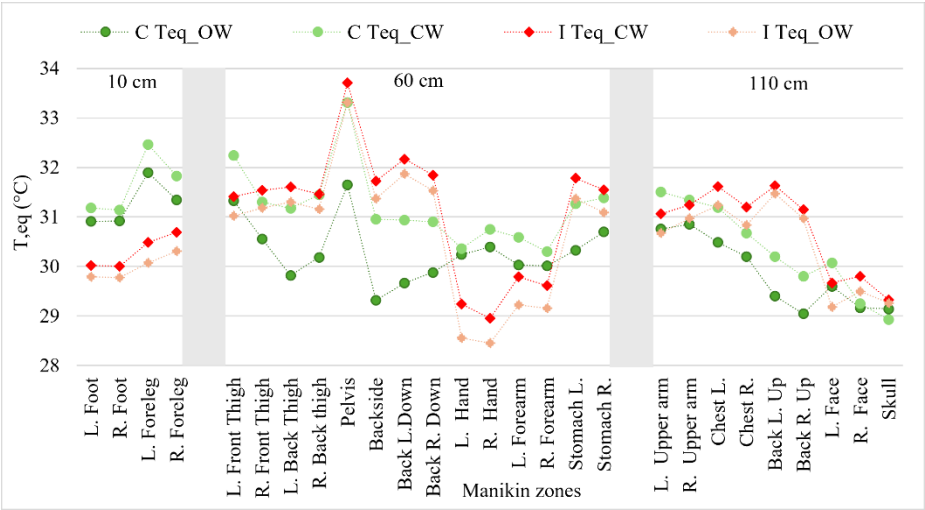

Fig. 10. Equivalent temperatures recorded by the thermal manikin in classrooms I and C for both test configurations (OW and CW)

4 Conclusions

An experimental campaign has been conducted on two classrooms equipped with decentralised mechanical ventilation systems, one with an internal unit within the classroom (I), and one with internal units and ducts located in the ceiling void (C). The results have demonstrated that:

- CO_2 levels are influenced by the combined opening of doors and windows. It was observed that opening only the windows does not result in an effective air exchange unless the door is also opened simultaneously in classroom I. In classroom C, the mechanical ventilation system alone is sufficient to ensure adequate IAQ.
- The three-dimensional comfort mapping, performed under steady-state conditions (closed doors and windows and constant ventilation system speed) during the intermediate season, shows that classroom I exhibits a point with a maximum air velocity that is 0.55 m/s higher than other areas of the classroom, while the air velocity in classroom C is homogeneous, with very small variations between maximum and minimum velocity points. In classroom I, temperatures are homogeneous at the center and lower at the edges of the room due to the asymmetry of the ventilation system's placement, while the air temperatures in classroom C are vertically stratified.
- The comfort analysis indicates that classroom I experiences discomfort, tending toward cold conditions, with a dissatisfaction rate of up to 50% near the mechanical ventilation unit. In contrast, classroom C does not exhibit any discomfort areas. Additionally, the thermal manikin showed that opening the windows improves the thermal conditions in the area near the teacher's desk in both classrooms. Specifically, the C system demonstrates lower and more comfortable average equivalent temperatures compared to the I system.

Based on the above findings, it can be concluded that the ventilation system with units and ducts hosted in the ceiling (C) is more effective in maintaining adequate CO_2 levels and providing better comfort conditions. Ongoing studies by this research group focus on the development of an intelligent, automated HVAC system capable of controlling CO_2 concentrations based on environmental conditions and user interactions with natural ventilation.

Acknowledgements

This research has received funding from the project Vitality – Project Code ECS00000041, CUP I33C22001330007 - funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.5 - 'Creation and strengthening of innovation ecosystems,' construction of 'territorial leaders in R&D' – Innovation Ecosystems - Project 'Innovation, digitalization and sustainability for the diffused economy in Central Italy – VITALITY' Call for tender No. 3277 of 30/12/2021, and Concession Decree No. 0001057.23-06-2022 of Italian Ministry of University funded by the European Union – NextGenerationEU.

This study is Non-Profit Co-financed byAgency (BANDOPNC. Projectcode: PREV-A-2022-12377013).

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Review

---------- REVIEW 1 ----------
SUBMISSION: 4126
TITLE: Mechanical ventilation and Indoor Environmental Quality: Experimental comparison between two decentralized systems in school classrooms
AUTHORS: Serena Summa, Margherita Cippitelli, Costanzo Di Perna and Francesca Stazi

The topic discussed in the paper is interesting. The paper structure is clear but to improve the paper the following points should be considered:

- in the introduction it is important to highlight that natural ventilation has an impact on acoustic comfort (in relation to the outdoor noise) and does not allow for filtration of the renewal air;

Thank you for this observation. This point has been introduced in Chapter 1, Introduction.

- the description of the HVAC systems of the case studies should be more detailed. Is type D a room equipped with an internal unit (temperature control) and

natural ventilation for IAQ control? Is type DI a room equipped with an internal unit in the false ceiling (temperature control) and natural ventilation for IAQ control? Are 500 and 750 mc/h related to air recirculation of the internal unit (fancoil)?

The authors thank the reviewer for this consideration that has helped us to make the text clearer to the readers. The heating system in both classrooms is provided by radiators, while the two mechanical ventilation systems are only responsible for ventilation and air renewal (thus the temperature is not controlled by either machine).
New details have been included in section 2.1, case study. To make the text more readable, the names of the two classrooms have been changed. The Falconara classroom is now called I (acronym for system with Internal unit) and the Recanati classroom is now called C (ventilation system inserted within the Ceiling).
In the new text we have explained in more detail that the type I machine is located inside the classroom and has two grilles on the machine itself: one for air intake and one for air extraction. The type C machine is installed in the false ceiling and the air intake and extraction take place through 4 helicoidal diffusers, two for the air intake and two for the extraction (also in the false ceiling), connected to the machine by ducts. The air flow rates for mechanical ventilation machines are 500 and 750 m^3/h for types C and I, respectively.
For what it's possible to understand, the air exchange in the rooms takes place only by opening the windows, is it correct? The air exchange in the rooms is due to both the mechanical ventilation machines (as these are always turned on during the analysed school hours) and the opening of the windows (natural ventilation).

- please define what do you mean for "decentralised system": is it related to the heat/cooling generation system only?

This information was added in section 2.1 in order to clarify the concept of decentralised mechanical ventilation. The new text is reported hereafter:" *The decentralised system, as opposed to the centralised system with only one large ventilation machine serving several rooms via ducts, is a system in which each room has its own ventilation machine sized with respect to the volume of air to be exchanged according to the national standard DM 18/12/1975 [40].*"

- Par. 2.1: please correct the date of decree 412;

Correction made.

- Fig. 1: the functional schemes are too small; these schemes could be integrated by highlighting the air renewal method of the rooms;

Figure 1 has been modified by enlarging the functional diagrams. Labels (in and out) have been added to the image to explain the operation of the two types of mechanical ventilation systems (I and C).

- Par. 3.2: it's not clear what is the CO2 source during the monitoring period; how many people are considered in the room? Please better specify this point;

By monitoring a period when students are in class and lessons are taking place regularly, the main source of CO2 is the students. Regarding the number of students occupying the two monitored classrooms, they are described in Table 1, where among the general data for the two classrooms, the 'number of students' is also reported.

- Par. 3.2: considering closed windows, is the effect of the internal units ventilation related to the distribution of CO2 in the room?

When the windows are closed, the CO2 levels depend on the presence of people in the classroom. The two classrooms analysed, each equipped with distinct mechanical ventilation systems, renew the air in different ways. The I system extracts and supplies air to the classroom through two vents on the unit. In contrast, the C system has two helical extraction grilles and two supply grilles, as can be seen in Figure 2.

- Par. 4.0: “In the classroom DI, the mechanical ventilation system alone is sufficient to ensure adequate IAQ”: as above, it’s not clear if the system provides also air renewal in the classroom.

This point in paragraph 4 refers to the results illustrated in paragraph 3.2, Figure 8. The phrase 'In the D classroom, the mechanical ventilation system alone is sufficient to ensure adequate IAQ' highlights how, with the air renewal guaranteed by this type of unit (now renamed C), it is possible to maintain an adequate IAQ for the analysed environment, i.e. the school, for which a maximum limit of 1350 ppm is established. To make this clearer, horizontal lines representing this limit have been added to the graphs showing the CO2 trends (Fig. 7 and 8), so that it is easier to see when this limit is exceeded.

- Par. 4.0: “the ventilation system with internal units and ducts (DI) is more effective in maintaining adequate CO2 levels”: if there is no air renewal, is this related only to the contaminants distribution in the classroom?

This study (as now clarified in the results in paragraph 3.2) evaluated the CO2 levels on a day when the mechanical ventilation systems were always turned on, and (in addition) the users opened/closed the windows freely. What is noticeable is that for the C system, when the windows are closed and therefore the air exchange is only guaranteed by mechanical ventilation, it is possible to keep the CO2 levels below the regulatory limit of 1350 ppm.

---------- REVIEW 2 ----------

SUBMISSION: 4126

TITLE: Mechanical ventilation and Indoor Environmental Quality: Experimental comparison between two decentralized systems in school classrooms

AUTHORS: Serena Summa, Margherita Cippitelli, Costanzo Di Perna and Francesca Stazi

The paper presents a comparison of two types of decentralised controlled mechanical ventilation systems in classrooms - one with a unit inside the classroom and one with an indoor unit and ducts placed in the ceiling void - taking into account the influences of opening and closing doors and windows during the course of the day, at specific periods of the school year.

The paper is very well organised according to a logical structure, comprising the following contents: an introduction and state of the art section, in which the gaps in the analyses found in the literature are stated in order to motivate the research objectives; methods a measurement instruments used for testing the two selected case studies; presentation and analysis of the results, by means of very clear and comprehensive graphs and tables; conclusions. Furthermore, the reference list is very robust and detailed and provides a solid basis for the development of the research objectives.

From the content point of view, I have no remarks. However, some minor formal

comments are reported below:
- In Table 1, it is recommended to use the same degree of approximation for the classroom/window area [m2], classroom height [m], and classroom volume [m3]. In addition, it is recommended to adopt the British/American system - as it was done in Section 3 - using the comma to indicate the thousands separator and the dot for decimals (for an order of magnitude of 10^4 or more).
Thank you for the correction. Table 1 has now been modified.
- In Section 2.2. "according to ISO 7730 standards [42], (Dantec in Figure 2).” the comma after the reference [42] must be removed.
The comma has been removed.
- In Figures 5 and 6, the colour nuances of the T(°C) and PMV scales seem not to correspond with those of the value ranges of the analysed areas, possibly because the image has been post-produced to improve readability. Please check.
The legends have now been corrected.
- The parameters "predicted mean vote (PMV)’ and "dissatisfaction percentages (PPD)" were introduced in section 2.2 and, therefore, in the following sections (3.1 and 3.3), they can be simply recalled by their acronym.
Thank you for the suggestion. Acronyms are used in all sections after section 2.2.
- Please check throughout the manuscript for consistency of terms in British or American English. For instance: in the title it is used “decentralized” and in section 3.2 “behavior” (US); in the abstract and within other sections it is used “analysed”, “decentralised”, “localised”, … (UK).
Now, all the terms are in British English. Thank you.
- In section 4, the second bullet point seems to be incomplete: “The three-dimensional comfort mapping, performed under steady-state conditions (closed doors and windows and constant ventilation system speed) during the intermediate season, SHOWS THAT Classroom D exhibits a point”.
The second point of paragraph 4 has been integrated.