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Assessment of Thermal Comfort and Indoor Air Quality in Library Group Study Rooms

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Abstract: Human performance and health are among the most relevant topics in modern society, especially at young ages, when academic performance is indispensable. Thus, as humans spend most of their life inside a building, thermal comfort and indoor air quality are essential aspects of a room. The aim of the current study is to numerically evaluate the main thermal comfort parameters such as PMV and PPD as well as indoor air quality, i.e., CO_2 concentration, in library group study rooms at the University of Gävle in Sweden. Rotroninc Measurement Solutions CL11 sensors were utilized for temperature measurements. Simulation models were created and validated based on building data as well as temperature measurements. Several simulations were conducted throughout the year, covering different periods. The results show that even though the ventilation system, with only temperature control, works as intended for maintaining thermal comfort, the CO_2 concentration rises above 1000 ppm when more than one student occupies the rooms, which is not recommended by different thermal comfort ruling institutions. Consequently, a modification to the ventilation system control is recommended, changing it from temperature control to CO_2 and temperature control.

Keywords: indoor air quality; thermal comfort; ventilation rate; CO_2 concentration; PMV; PPD; IDA ICE

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Citation: Ameen, A.; Bahrami, A.; Elosua Ansa, I. Assessment of Thermal Comfort and Indoor Air Quality in Library Group Study Rooms. *Buildings* **2023**, *13*, 1145. https://doi.org/10.3390/buildings13051145

Academic Editors: Chi-Chung Lee, Kin Wai Tsang, Asiri Umenga Weerasuriya, Yaohan Li and Xuelin Zhang

Received: 30 March 2023
Revised: 21 April 2023
Accepted: 24 April 2023
Published: 25 April 2023

1. Introduction

Comfort and health are everyday life issues. Furthermore, humans spend most of their lives in closed environments, some of which require healthy working environments such as classrooms or working offices [1]. One of the most studied fields has always been thermal comfort and indoor air quality conditions of rooms. As the importance of safe and comfortable study and working environments has increasingly been gaining attention to improve performance in every aspect of life, there is an increasing interest in evaluating thermal comfort and indoor air quality in these places. Moreover, the need for having good study and working spaces for the productiveness of students/occupants is important from an academic point of view, which makes the current research on thermal comfort and indoor air quality even more interesting and relevant.

Human performance under different environmental conditions has been evaluated in past decades. One of the important aspects of evaluating indoor air quality in space is to evaluate the carbon dioxide (CO_2) concentrations and duration levels [2,3].

In 2022 Shrestha et al. [4] used CO_2 to evaluate the indoor air quality (IAQ) as an indicator in naturally ventilated Nepalese school buildings. Yang et al. [5] used CO_2 as one of several indicators to predict the IAQ in healthy building design by developing a simulation toolbox named i-IAQ. Stabile et al. [6] assessed the air quality in an Italian classroom by evaluating the CO_2 concentrations in relation to the energy usage of the ventilation system. In a review article by Saini et al. [7], the authors found that 70% of the studied research papers, of a total of 141, focused on monitoring CO_2 concentration as an indoor air quality parameter. This shows that CO_2 concentration in the occupied space is commonly used in determining indoor air quality in working or school environments [8].

In a study by Asif & Zeeshan [9], the IAQ was evaluated by monitoring the temperature, relative humidity, and CO_2 concentration in classrooms during two seasons. When comparing the results with the ASHRAE standards, it was observed that the indoor CO_2 concentrations exceeded the recommended levels more than 50% of the time during occupancy hours for all the classrooms. The CO_2 concentration increased considerably during weekdays compared with weekends. However, regardless of the weekdays, when students were in the room, the CO_2 concentration increased considerably over the stated recommended limit of 1000 ppm. Nonetheless, during the breaks, which means no students are in the rooms, the CO_2 concentration fell slightly and increased again when students were back in the room.

According to the Swedish Work Environment Authority's regulation [10] and ASHRAE Standard [2], indoor CO_2 concentration should be below 1000 ppm to avoid the negative effects of poor air quality.

An observational study by Crosby et al. [11] showed that at indoor temperatures of 23.5 °C, the probability of an occupant feeling thermally satisfied at a measured CO_2 concentration of 550 ppm was 0.62. This value decreased to 0.28 at 750 ppm. Therefore, the interdependence between thermal satisfaction, leading to thermal comfort, and CO_2 concentration appears to be strong.

In terms of evaluating the thermal comfort in an occupied space, two common indices are widely used in the scientific community, Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD).

The PMV and PPD standard is defined both in ISO 7730 [12] and ASHRAE Standard 55-2020 [13] and was developed by P.O. Fanger by sampling responses from occupants regarding thermal comfort under controlled conditions [14].

The PMV is the "Predicted Mean Vote" of thermal comfort by large group occupants under the same thermal conditions. The PMV vote is classified by a 7-step scale: −3 (cold), −2 (cool), −1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), and +3 (hot).

The PMV model combines four physical variables, which are air velocity, air temperature, mean radiant temperature, and relative humidity, and two additional parameters which are related to the occupant: clothing insulation and activity level [15]. The other index PPD quantifies the percentage of dissatisfied persons with the indoor climate. These indices have been used in previous research that has evaluated thermal comfort in occupied spaces.

In a study by Sarbu et al. [16], the thermal comfort and indoor air quality were assessed based on PMV and PPD indices as well as CO_2 concentration using subjective and experimental measurements in two air-conditioned classrooms at a university. These indices were also used by other research teams [17–19] to evaluate the thermal comfort of students in classrooms.

In order to obtain an optimal level of indoor air quality and thermal comfort, different ventilation strategies can be deployed.

According to Rismanchi et al. [20], variable air volume (VAV) ventilation systems are effective; however, due to the stratification and formation of pollutant pockets, setpoints are often misread. Thus, the ventilation system works much more than needed, leading to increased energy usage. Accordingly, different control methods are proposed for the improvement of the ventilation system, such as duct pressure-based control strategies, CO_2 concentration-based strategies, fault-tolerant control strategies, and room pressure control strategies. Furthermore, proper control of the VAV ventilation system can lead to 30% energy savings and, more importantly, to better control of the indoor air quality regarding CO_2 concentration and temperature stratification. However, by testing different advanced machine-learning algorithms, it has been found that its use can generate up to 51% energy savings with no major investment needed but for software implementation and its controller [21].

This study concerns the indoor air quality and thermal comfort assessment of two study rooms in the library of the University of Gävle in Sweden. The main objective of the study is to examine if the environmental conditions in these rooms are good and stable enough for their intended design and purpose. In addition, the evaluation will focus on suggesting different strategies for controlling the ventilation flow rate to increase thermal comfort and indoor air quality. The result of this study is obtained from numerical simulations based on validated models.

2. Object for Study

The study focused on two study rooms on the top story (4th floor) of the University of Gävle's library. Regarding the rooms' dimensions, they are configured as a 4-person room (Room 23:425) and a 6-person room (Room 23:429). However, the used heating and ventilation systems are the same type. The University of Gävle is located in the mid-Sweden. Thus, the climate during the cold season is harsh, especially during winter. However, the experimental study (temperature measurements) was carried out in spring during the month of April. Thus, the climate was not that cold. On average, the outdoor temperature during April was between 5 °C and 10 °C. On the other hand, the rooms are located on the North facing side of the library building, which means that there is almost no incident solar radiation, as can be seen in Figure 1.

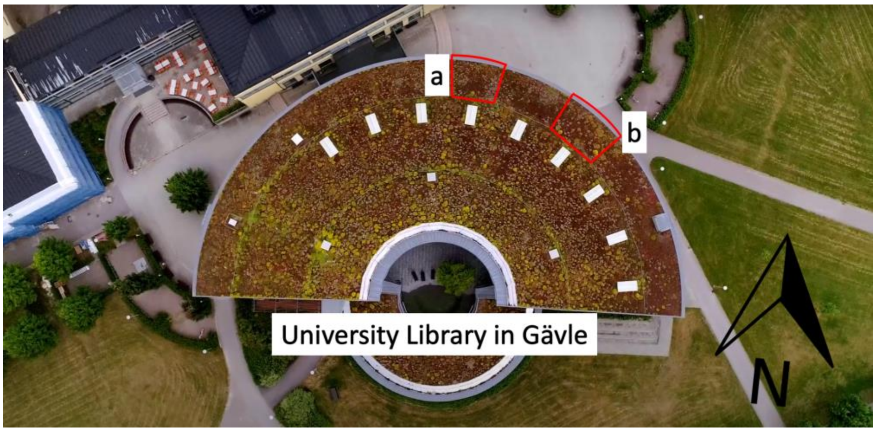

Figure 1. Satellite image of the University of Gävle's library and the red marked locations are the studied rooms. (**a**) is Room 23:425 and (**b**) is Room 23:429.

Although the rooms' dimensions are different, they have a common shape which can be observed in Figure 2. Two different widths can be found, the smaller one (b) and the larger one (B), and the same for the height (h and H). The length (l) of the rooms is the same.

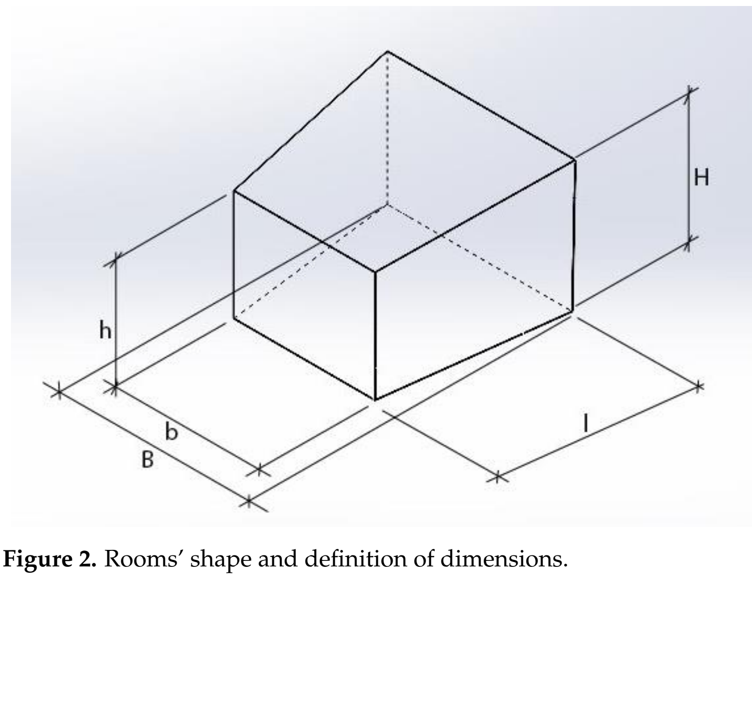

Figure 2. Rooms' shape and definition of dimensions.

The walls of both rooms are the same. Figure 3 illustrates the details of the external wall (North-facing wall). As the figure shows, the wall is made of 90 mm concrete, 170 mm cellular plastic, 70 mm concrete, and 20 mm plaster [22]. In this way, the U-value calculated for the exterior wall was 0.221 W/m^2·K for both rooms. However, the main part of the external wall is covered by 2-glazed windows in both rooms.

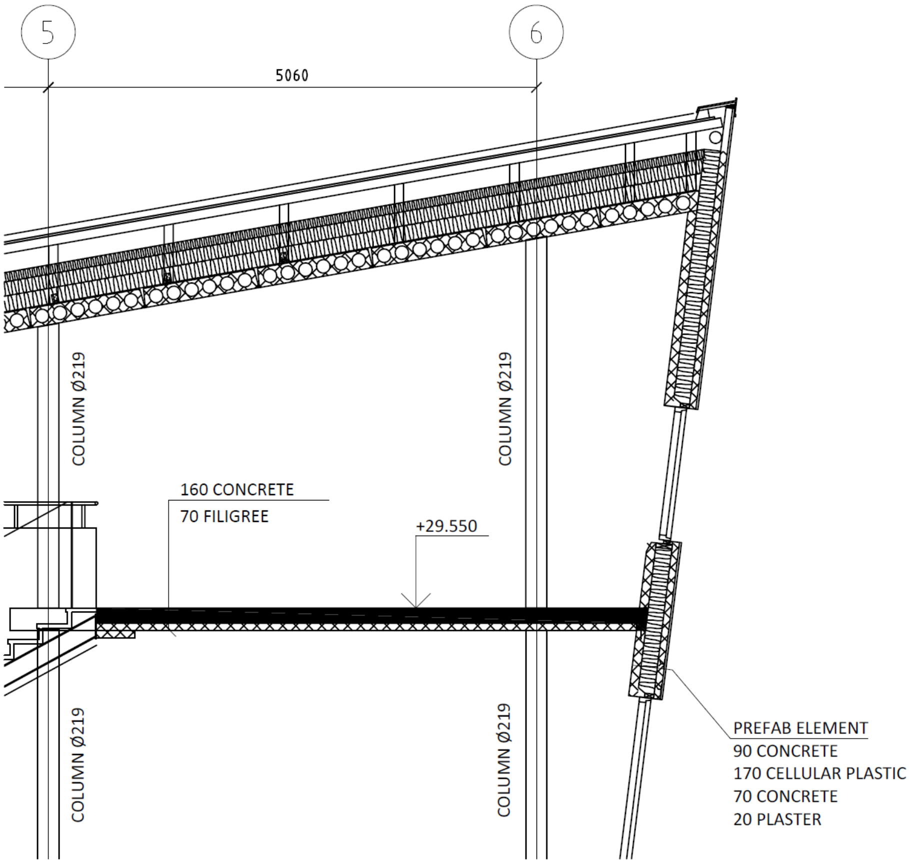

Figure 3. Details of the external wall.

Meanwhile, according to Figure 4, the roof consists of different layers. From the outside to inside, the roof is made of 30 mm Xeroflor sedum-moss, 20 mm Grodan layer, 22 mm wood sheet, 300 mm air gap, 430 mm mineral wool, and 200 mm hollow core slab. The material's thermal properties of the rest of the layers were not considered owing to their small thickness or practically non-existing thermal conductivity values. Thus, the U-value for the roof was obtained at 0.071 W/m^2·K for both rooms.

The structural layers of the floor are displayed in Figure 5. The floor, which is the ceiling for the rooms on the third floor, is built from a 130 mm furnishing material, 0.2 mm foil, 160 mm concrete layer, and 70 mm filigree. Because the temperature on the other side of the floor is the same as the indoor temperature, the heat transfer through it was not considered.

The details of interior wall, the wall between the room and the library's main study space, is made from two layers of glass and wood, both 122 mm thick, without insulation, as its main goal is esthetics. This interior wall's U-value was 5.90 W/m^2·K for both rooms. However, as the temperature on the other side of the walls was the same as in the measured rooms, hence the heat transfer was not considered.

Nevertheless, it is necessary to describe both rooms separately, as the equipment and their positioning were different for them.

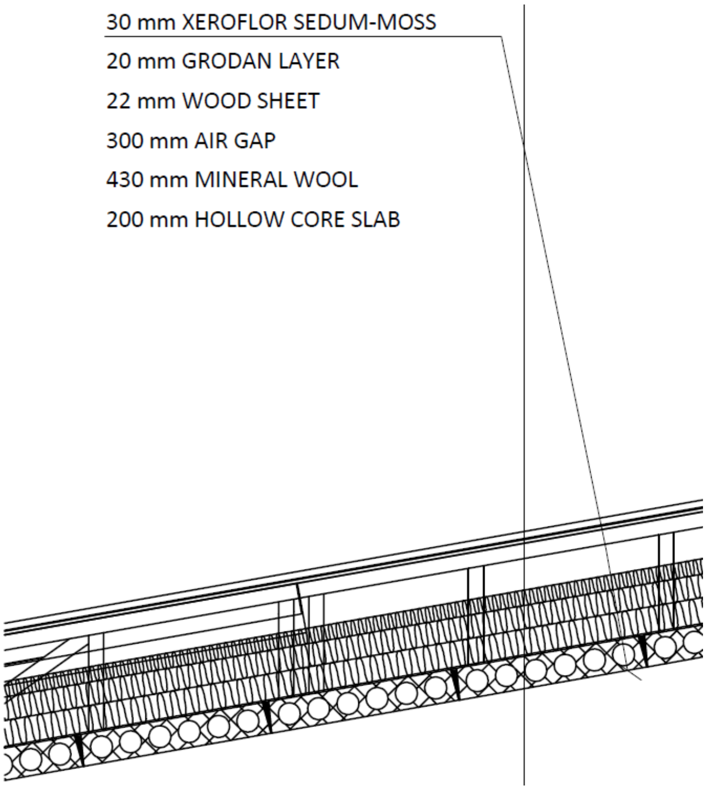

Figure 4. Details of the roof.

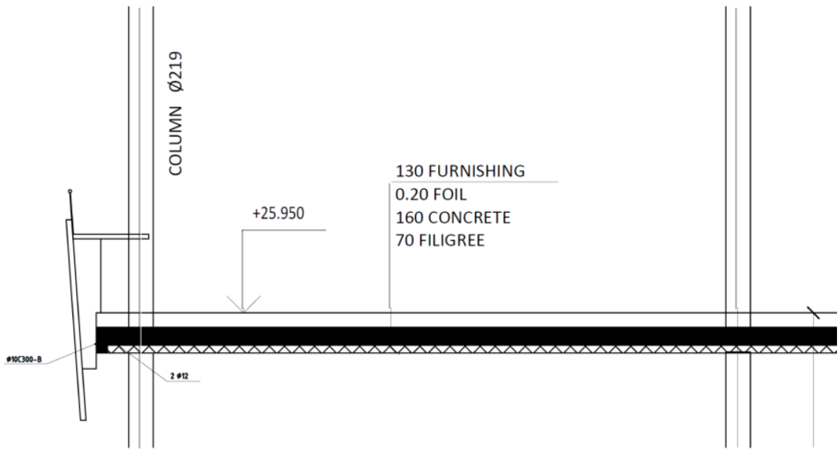

Figure 5. Details of the floor.

2.1. Room 23:425

Room 23:425 has a volume of 30.73 m^3 with l, B, b, h, and H, respectively, as 3.26 m, 2.54 m, 2.39 m, 3.44 m, and 4.02 m. The plan of the room is depicted in Figure 6. It has a 2-glazed window with a 3.24 m^2 surface facing North, as well as a table and four chairs for students. For this room, a small window is also located on each exterior wall with a connection to the adjacent rooms. Each of these small windows has an area of 0.63 m^2, and both are 2-glazed. The room is also equipped with two 11 W fluorescent lamps.

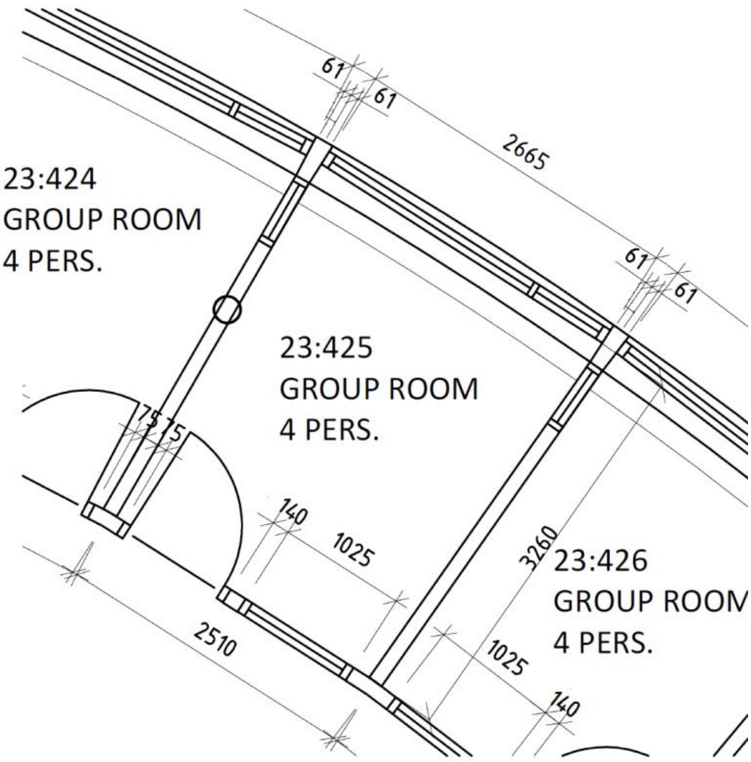

Figure 6. Plan of Room 23:425.

The system used for ventilation is a variable flow rate (VFR) system, Lindlab Polaris I. According to the building's documentation, the ventilation system for this room is controlled by the temperature. The system also has a built-in cooling capacity of 2450 W when there is a need for cooling during warmer periods.

The heating system consists of a radiator located under the window, with the length nearly from side to side of the room. The total length and height of the radiator are 1.8 m and 0.3 m, respectively. The radiator thermostat is configured to maintain a temperature between 21 °C and 22 °C in the room.

The number of occupants in the room was set to 4. However, it has been seen that most of the time, only two students use the rooms.

2.2. Room 23:429

The second study room is made to accommodate six people, larger than Room 23:425. The composition of the room is similar to the smaller one, Room 23:425. The dimensions of the room are b = 3.36 m, B = 3.92 m, l = 3.26 m, h = 3.44 m, and H = 4.02 m, as shown in Figure 7. The lighting system consists of two 11 W lamps. The ventilation system is a VFR system, and the heating system consists of the same type of radiator installed under the windows. The radiator in this room is 3 m long and 0.3 m tall. The material compositions of the walls are the same as the smaller room. However, the surfaces are bigger (except the sidewalls). Moreover, there is just one intermediate wall having a window with the same surface as the other room since this room only has one adjacent room. Once again, the window is facing the North direction primarily. Therefore, there is almost no direct solar radiation incidence. The surface of the window is 4.5 m^2.

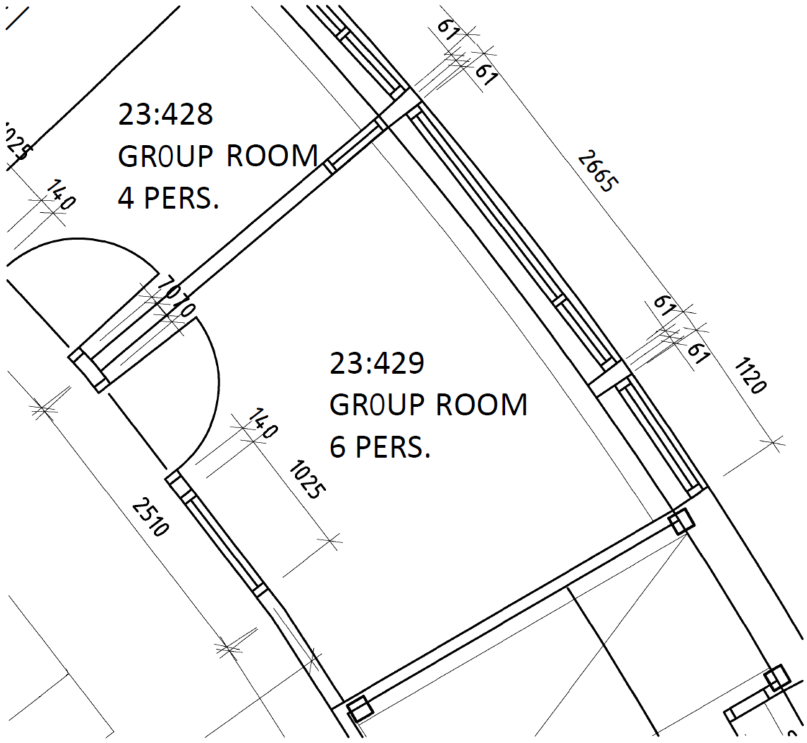

Figure 7. Plan of Room 23:429.

3. Methods

This section is divided into several subsections. The data collection deals with the placement of sensor in the library rooms. The onsite temperature measurements were conducted during the month of April 2022 and were used to validate a numerical model.

3.1. Data Collection

Temperature data were collected by using two Rotroninc Measurement Solutions CL11 sensors, one placed in each room. This sensor is shown in Figure 8. The sensors were positioned in the corner of the rooms, employing cable ties hanging from a coat rack facing the inner side.

Figure 8. Rotroninc Measurement Solutions CL11 sensor for collecting temperature.

From the manufacturer, it is known that the measuring range is −20 °C to +60 °C for the temperature range. Moreover, the accuracy of the device at 23 °C is ±0.3 °C for temperature measurements. For this study, these values are valid, as the indoor temperature of the rooms is usually between 18 °C and 28 °C [23].

3.2. Building Simulation Software

In order to evaluate specific indices such as PMV and PPD [24], software called IDA ICE v. 4.8 SP2 was used. IDA Indoor Climate and Energy (IDA ICE) is a dynamic single and multi-zone simulation software used for evaluating or predicting the energy use of a building, as well as the thermal comfort and indoor air quality (CO_2) inside a building [25]. The software has been validated according to several standards, such as CEN standards EN 15255-2007 [26], 15265-2007 [26], and ASHRAE Standard 140-2004 [27]. The software has also been validated in a study by Woloszyn & Rode [28]. IDA ICE has been used in Scandinavian countries for simulating energy performance estimates and thermal comfort evaluations [29–31].

3.3. Numerical Model Validation

A validation study was conducted to compare the temperature that was measured for 3 days, 15 April 2022–17 April 2022, against the simulated results. The simulated and the experimental results were in good agreement, as can be seen in Figure 9. ASHRAE Guideline 14-2002 [27] was used to calibrate numerical models. This was conducted by calculating two principal uncertainty indicators or errors, *NMBE* and *CV(RMSE)*, which are shown in Equations (1) and (2) below:

$$NMBE = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n - p} \times 100\ (\%) \quad (1)$$

$$CV(RMSE) = \frac{1}{\overline{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n - p}} \times 100\ (\%) \quad (2)$$

where m_i is the measured value, s_i is the simulated value, n is the total number of measured data points, p the number of adjustable model parameters and $\overline{m}$ is the mean of the measured value. Table 1 shows the calibration criteria according to ASHRAE Guideline 14-2002.

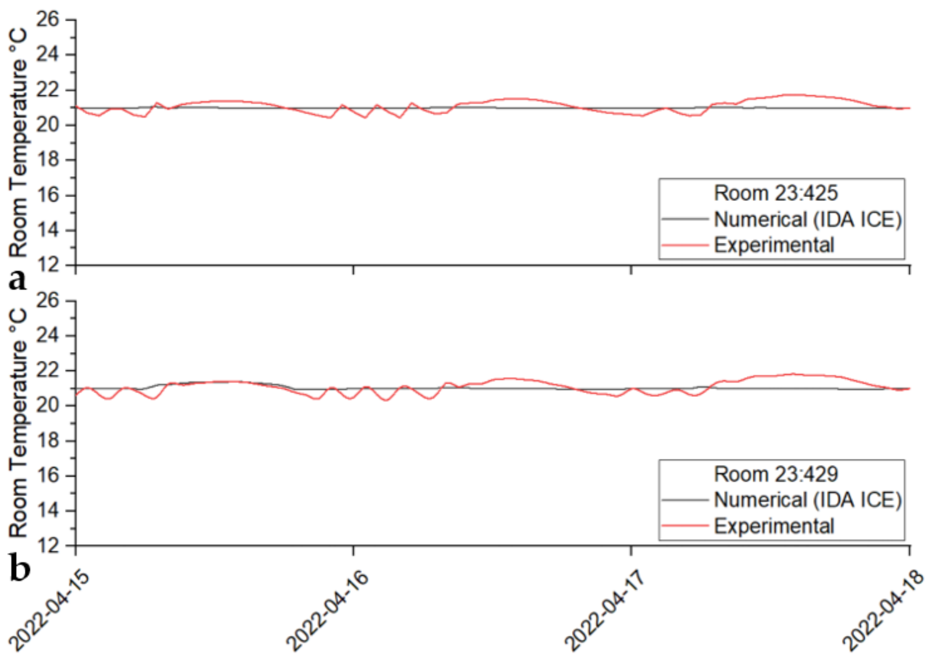

Figure 9. (**a**) Validation results for the numerical model of Room 23:425 and (**b**) for Room 23:429.

Table 1. The calibration criteria according to ASHRAE Guideline 14-2002 [27].

Calibration Criteria (%)	Index	ASHRAE Guideline 14-2002
Hourly criteria	NMBE CV (RMSE)	±10% 30%

Table 2 shows the hourly calibration indices for both of the room's temperatures. The results show that the difference between the experimental and numerical values are within the acceptable range based on ASHRAE Guideline 14 when using the hourly criteria.

Table 2. The calculated calibration indices for the air temperature in rooms 23:425 and 23:429 based on hourly measurements.

Uncertainty Indices	Air Temperature in Room 23:425	Air Temperature in Room 23:425
NMBE (%)	0.4%	0.5%
CV (RMSE) (%)	1.8%	1.9%

3.4. Simulation Model and Boundary Conditions

The base models used in this study are displayed in Figure 10. The models were built according to the detail given in Section 2, which also lists the specific material and composition of the walls. The detailed structural components and properties of the building are shown in Tables 3 and 4.

Table 3. Thermal transmittance of building's structural components and general data.

Structural Component	U-Value (W/(m^2·K))
External wall	0.221
Side walls	0.174
Internal floor	0.793
Internal wall	5.90
Roof	0.071
Heated floor area for room 23:425	8.43 m^2
Room 23:425 volume	31.61 m^3
Window-to-Wall Ratio for room 23:425	30.3%
Heated floor area for room 23:429	11.85 m^2
Room 23:429 volume	44.51 m^3
Window-to-Wall Ratio for room 23:429	28.6%

Table 4. Detailed properties of the window.

Type	U-Value (W/(m^2·K))	g-Value	Transmitted Visible Light
Double-Pane Window	2.30	0.76	0.81

Once the building was finished and the relevant input data and boundary conditions were inserted, a one-year simulation, broken up into several weekly-based simulations, were conducted for both of the rooms. The climate file for the city of Gävle was used, which is based on data from the Swedish Meteorological and Hydrological Institute (SMHI). The rooms were simulated with different occupancy loads, 1–6 persons for room 23:429 and 1–4 persons for room 23:425. The focus of the simulation results was to evaluate thermal comfort and indoor air quality based on the number of occupants in combination with three different ventilation control systems. The input data for the building are listed in Tables 3 and 4. The occupants ranged from 1–6 occupants depending on the case and room occupancy. Each occupant generated heat equivalent to 90 W, and each room was equipped with 22 W of lighting. It is worth mentioning that the simulation model assumes no heat transfer through the internal wall, side walls, and floor since these walls and the floor are simply facing rooms with a similar temperature. The rooms are equipped with a hot water radiator with a maximum power of 650 W for room 23:425 and 900 W for room 23:429 for heating. A cooling panel on the ceiling is also included, with a cooling capacity of 2450 W in each room for cooling purposes during the cooling season. These radiators and the cooling panels are proportional-integral (PI) controlled. The ventilation system of the model is configured as a VAV that is controlled by either room temperature, CO_2 concentration, or both of them combined. Detailed air flow rate settings for the ventilation supply air are shown in Table 5.

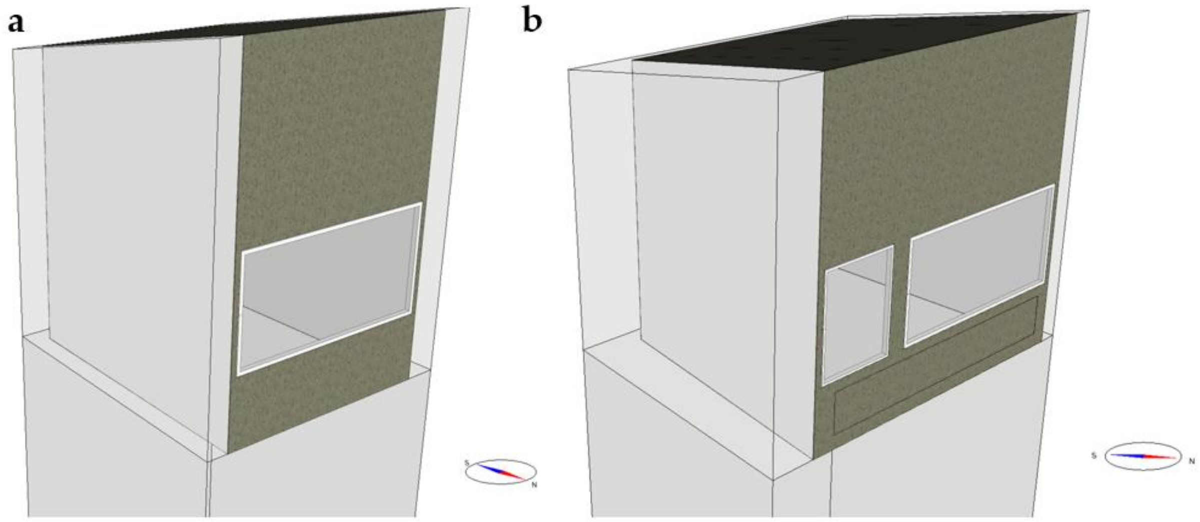

Figure 10. (**a**) IDA ICE model for room 23:425 and (**b**) room 23:429.

Table 5. Software control setpoints for ventilation supply settings.

Parameter	Value		Unit
	Minimum	Maximum	
Control Setpoint			
Temperature	22	25	°C
Relative Humidity	20	80	%
CO_2 Concentration	600	1000	ppm
Control Setpoint Room 23:425			
Mech. Supply Air Flow	0.35 *	3.77 *	L/(s·m^2)
Mech. Return Air Flow	0.35 *	3.77 *	L/(s·m^2)
Control Setpoint Room 23:429			
Mech. Supply Air Flow	0.35 *	3.99 *	L/(s·m^2)
Mech. Return Air Flow	0.35 *	3.99 *	L/(s·m^2)

* These values are set based on configuration settings in the AHU.

The supply air temperature is set according to Figure 11. The supply air temperature is set to 18 °C when the outdoor temperature is ≤13 °C. When the outdoor temperature is between >13 °C and ≤18 °C, the supply air temperature is linearly lowered between 18 °C and 12 °C. Once the outdoor temperature is greater than 18 °C, the supply air is kept at 12 °C. A schedule was also applied for when the rooms are being occupied by students as well as the use of lighting, which is shown in Figure 12. It is worth mentioning that the vertical axis in Figure 12 shows the fraction of occupancy or lightning power applied to the room.

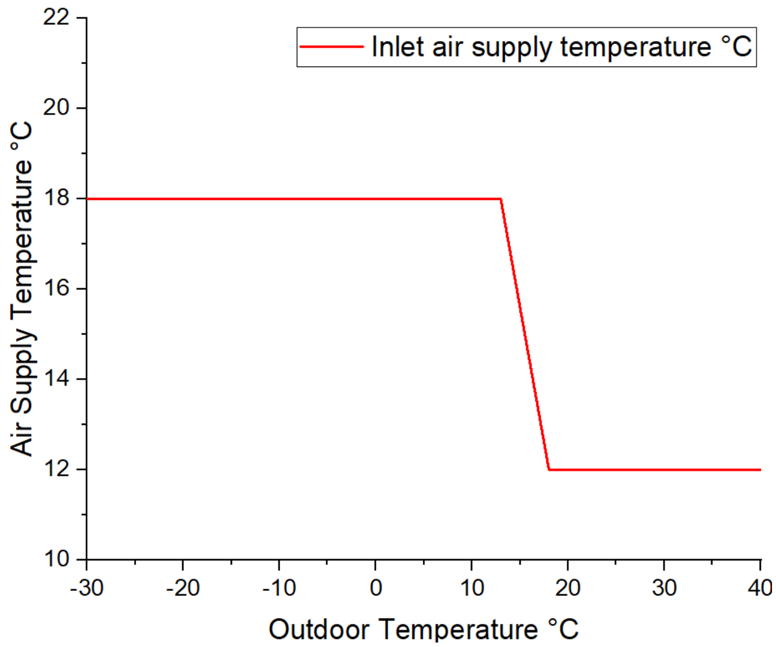

Figure 11. The configured air supply temperature in relation to the outdoor temperature set in the air handling unit in IDA ICE.

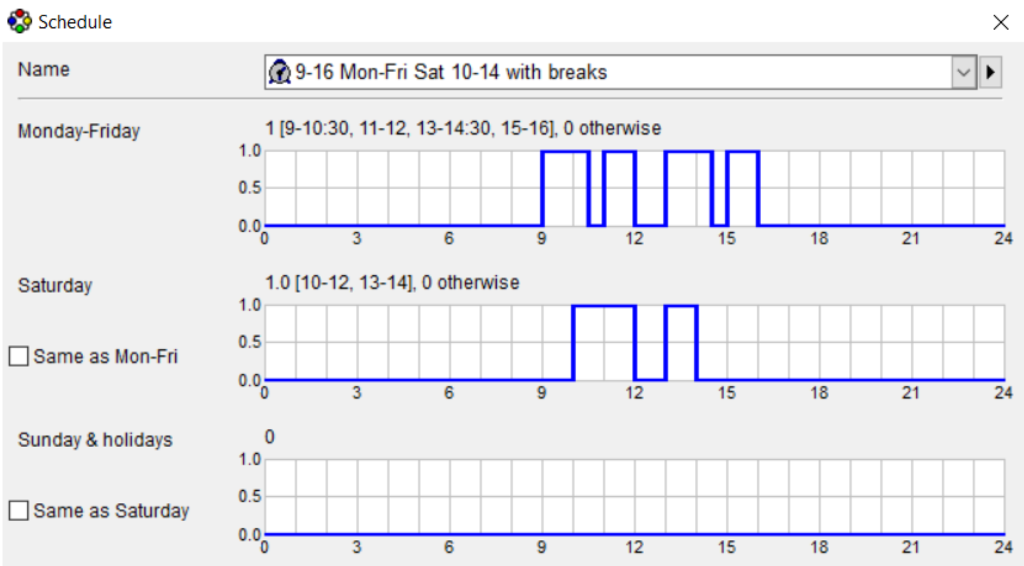

Figure 12. The schedule for occupancy and lighting for the study rooms.

The activity levels for the occupants are set to 1.0 MET, and the clothing value is set to 0.75 ± 0.25 CLO. The infiltration was chosen to be according to the wind-driven flow with an air tightness of 0.3 L/(s·m^2 external surface) at a pressure difference of 50 Pa.

A total of 30 cases were evaluated based on room, the number of occupants, and ventilation control, which are shown in Table 6.

Table 6. Case settings for study rooms.

Case	Room	Occupant	Ventilation Control
1	23:425	1	Temperature
2	23:425	2	Temperature
3	23:425	3	Temperature
4	23:425	4	Temperature
5	23:429	1	Temperature
6	23:429	2	Temperature
7	23:429	3	Temperature
8	23:429	4	Temperature
9	23:429	5	Temperature
10	23:429	6	Temperature
11	23:425	1	CO_2
12	23:425	2	CO_2
13	23:425	3	CO_2
14	23:425	4	CO_2
15	23:429	1	CO_2
16	23:429	2	CO_2
17	23:429	3	CO_2
18	23:429	4	CO_2
19	23:429	5	CO_2
20	23:429	6	CO_2
21	23:425	1	Temperature + CO_2
22	23:425	2	Temperature + CO_2
23	23:425	3	Temperature + CO_2
24	23:425	4	Temperature + CO_2
25	23:429	1	Temperature + CO_2
26	23:429	2	Temperature + CO_2
27	23:429	3	Temperature + CO_2
28	23:429	4	Temperature + CO_2
29	23:429	5	Temperature + CO_2
30	23:429	6	Temperature + CO_2

The orientation of the rooms was set at 10° NE for room 23:425 and 40° NE for room 23:429. No blinds or shading were used for the windows in the model, and there was no possibility for the occupants to open the windows. In order to evaluate the thermal comfort and indoor air quality over the entire year, one week was singled out for each month. The dates and times are shown in Table 7.

Table 7. Evaluated dates and times for the simulation for one year.

Date	Day & Time
10–15 January	Monday–Friday 9–16, Saturday 10–14
14–19 February	Monday–Friday 9–16, Saturday 10–14
14–19 March	Monday–Friday 9–16, Saturday 10–14
4–9 April	Monday–Friday 9–16, Saturday 10–14
9–14 May	Monday–Friday 9–16, Saturday 10–14
13–18 June	Monday–Friday 9–16, Saturday 10–14
11–16 July	Monday–Friday 9–16, Saturday 10–14
15–20 August	Monday–Friday 9–16, Saturday 10–14
12–17 September	Monday–Friday 9–16, Saturday 10–14
10–15 October	Monday–Friday 9–16, Saturday 10–14
14–19 November	Monday–Friday 9–16, Saturday 10–14
12–17 December	Monday–Friday 9–16, Saturday 10–14

4. Results and Discussion

In this section, the obtained results from the simulation periods for both rooms are presented and discussed.

4.1. Results for Room 23:425

When evaluating the statistical values of PMV for Room 23:425 for January month (Figure 13a), the results showed that when one occupant was in the room, the different ventilation strategies performed very similarly. The results showed the median PMV values for Case 1, Case 11, and Case 21 were −0.582, −0.611, and −0.585, respectively. In terms of PPD, these values were 12.1, 12.8, and 12.2%, as shown in Figure 14a. The maximum difference between all three cases was 0.7%. When comparing the CO_2 concentration, as shown in Figure 15a, the results showed that Case 1 was above the recommended value for 1000 ppm and that not having any CO_2 control at all drastically reduced the indoor air quality in the room. The median CO_2 results for Case 1, Case 11, and Case 21 were 1103, 714, and 996 ppm, respectively. The maximum difference between Case 1 and 11 was 389 ppm (35.3%) which is significant. However, this reduction in CO_2 concentration and increase in air quality comes with a cost, which is a higher supplied air flow rate. The median air supply flow rate results for Case 1, Case 11, and Case 21 were 2.95, 8.39, and 3.58 L/s, respectively, as shown in Figure 16a.

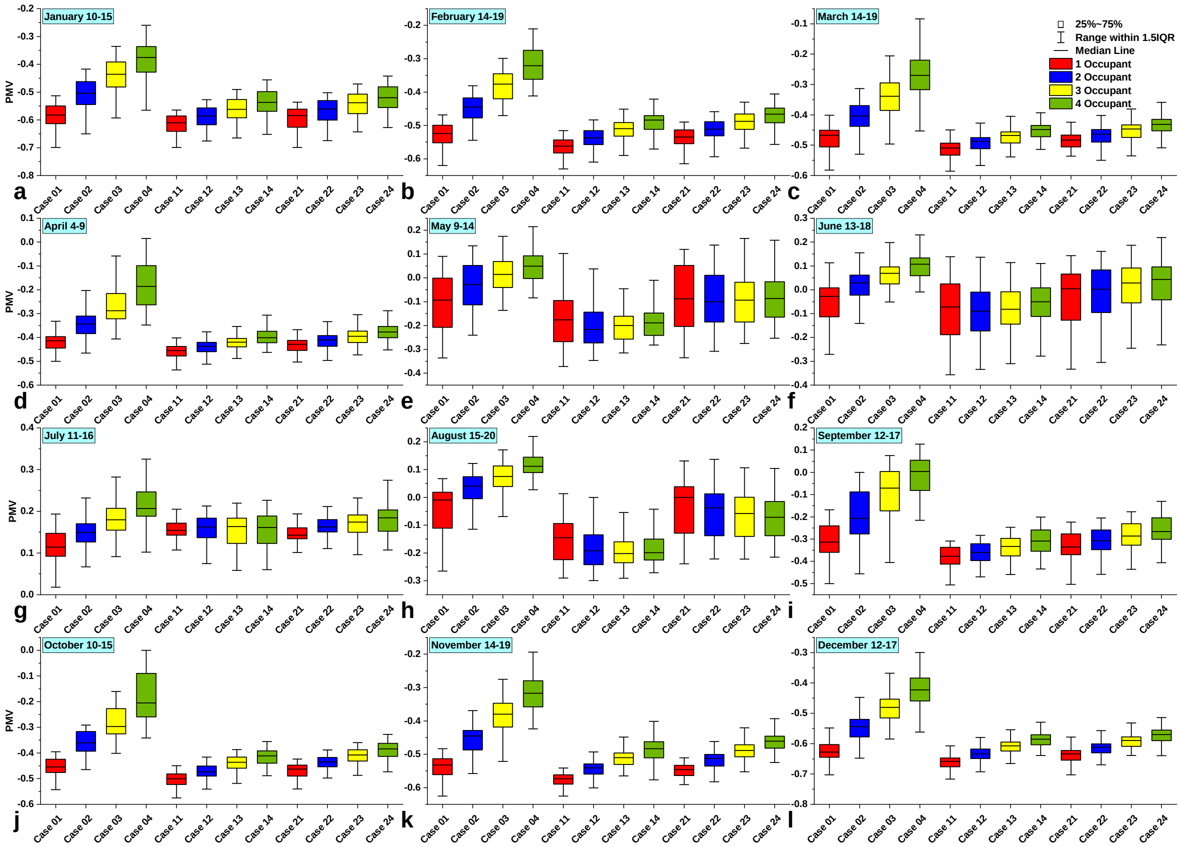

Figure 13. PMV evaluation for Room 23:425 with 1–4 occupants during various time periods.

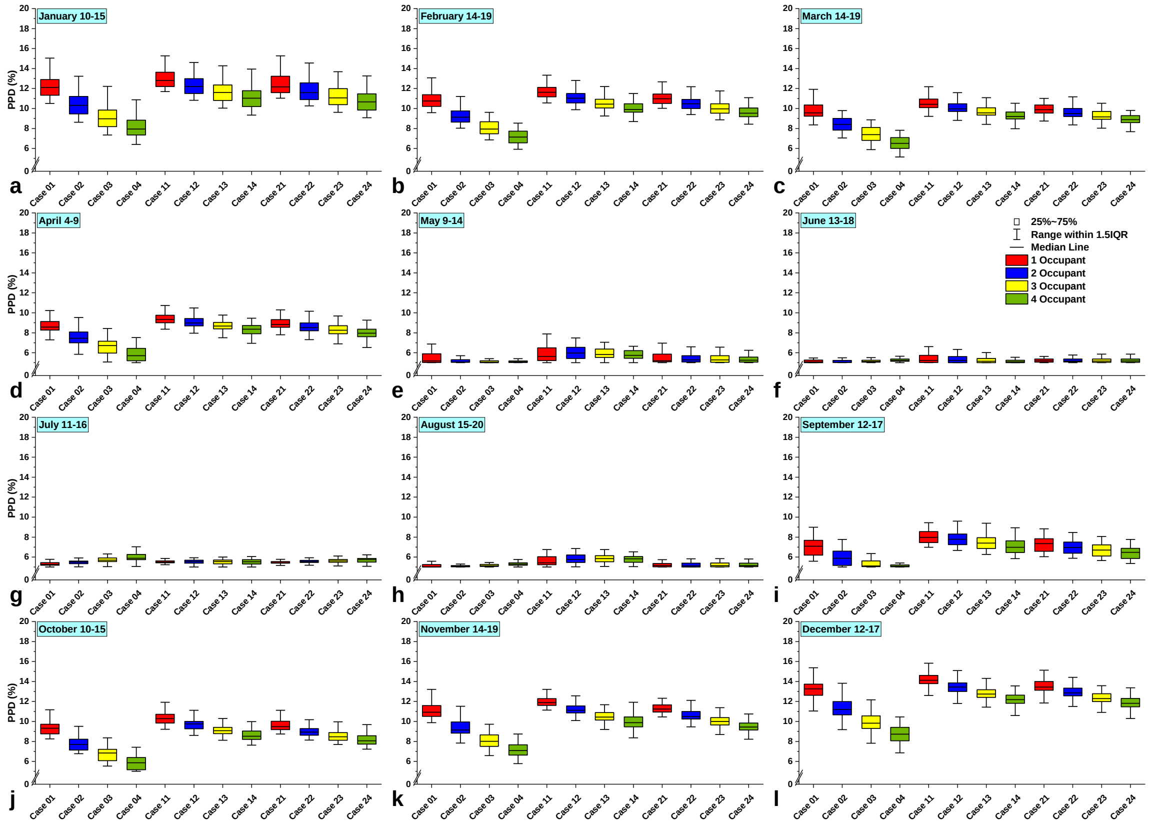

Figure 14. PPD evaluation for Room 23:425 with 1–4 occupants during various time periods.

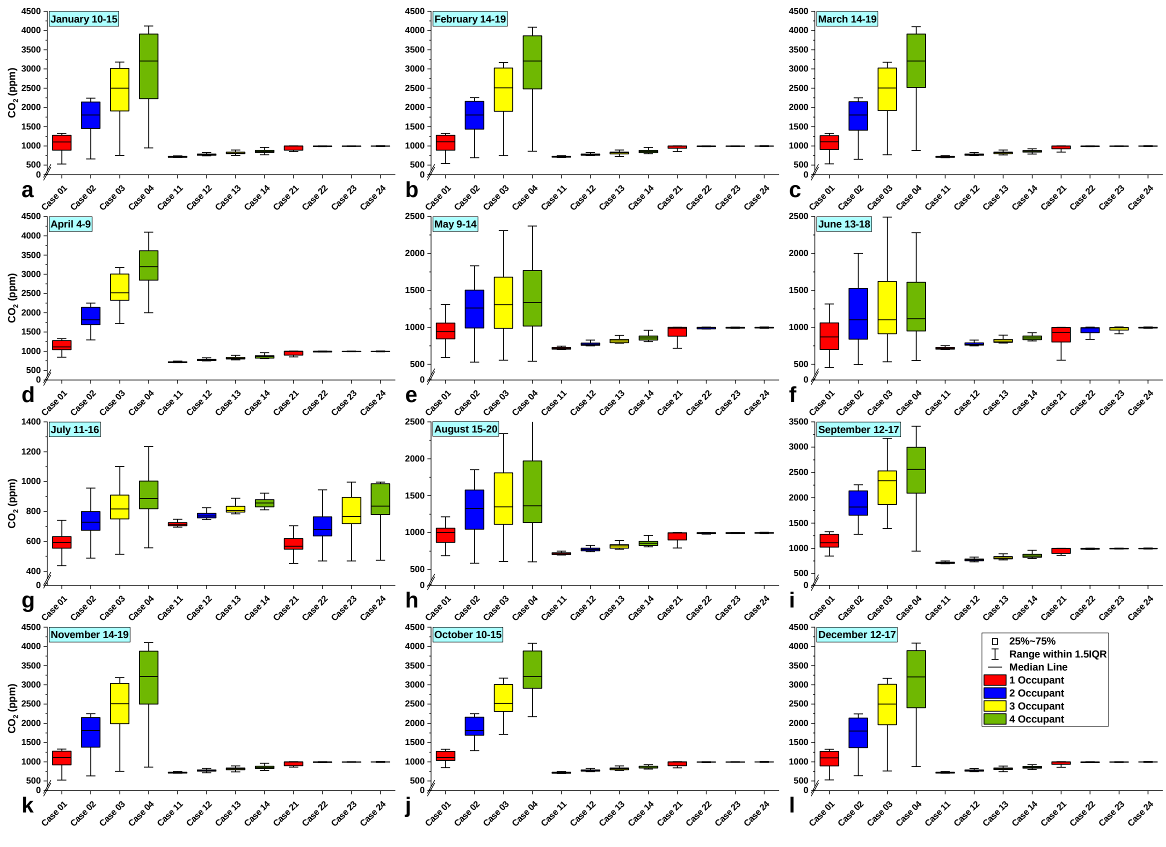

Figure 15. CO_2 evaluation for Room 23:425 with 1–4 occupants during various time periods.

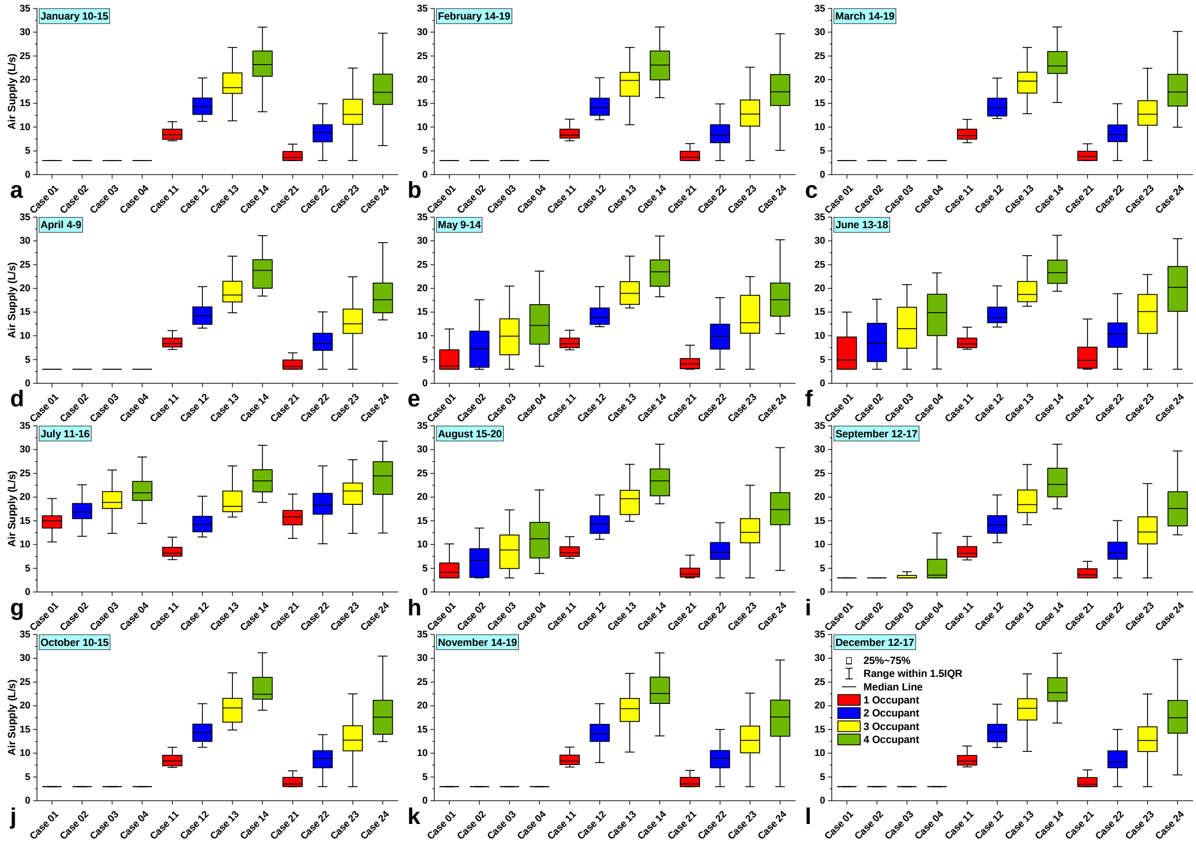

Figure 16. Air supply flow rate for Room 23:425 with 1–4 occupants during various time periods.

When increasing the occupancy to two persons, the results showed slightly improved PMV values for all cases, as shown in Figure 13a. The results showed that the median PMV values for Case 2, Case 12, and Case 22 were −0.504, −0.586, and −0.561, respectively. In terms of PPD, these values were 10.3, 12.2, and 11.6%. The median CO_2 results for Case 2, Case 12, and Case 22 were 1806, 775, and 996 ppm, respectively. These results showed that when increasing the occupancy above one, the ventilation that is only controlled by temperature does not act quickly or sufficiently to improve indoor air quality. Once again, this comes with the cost of an increased ventilation flow rate. When comparing Case 1 vs. Case 2 (e.g., 1 vs. 2 occupants), when controlled by only the temperature, the ventilation flow rate does not change (2.95 vs. 2.95 L/s). However, when comparing Case 11 vs. Case 12, the ventilation flow rate is increased from 8.39 to 14.34 L/s when the ventilation system is CO_2 controlled and from 3.58 to 8.89 L/s (Case 21 and Case 22) when the ventilation system is temperature & CO_2 controlled. Further evaluation of the other Cases (Case 3–4, Case 13–14, and Case 23–24) showed similar behavior in that the system with a CO_2 sensor increased the flow rate to reduce the CO_2 concentration in the room. It is worth mentioning that the increase in flow rate for the CO_2-controlled ventilation systems created a slightly colder environment, as can be seen by the PMV results. The reason for this is that the supply air temperature is only 18 °C, which is a few degrees colder than the average room temperature. It can also be seen that when the occupancy is increased to 2, 3, and 4 persons, the ventilation system that is only controlled by temperature is not a viable option as the CO_2 concentration becomes very high. For example, when having 3 and 4 people in the room, the median CO_2 concentration will reach 2503 and 3209 ppm, respectively. This level is much higher than the recommended value of 1000 ppm.

When looking at February, March, and April (Figure 13b–d), the results showed a similar development as for January month. However, when evaluating May month (Figure 13e), the results showed a more spread-out distribution of PMV. This is related to a wider spread of temperature during the day and the impact of indirect solar radiation through the windows. As can be seen, the median PMV values have also increased, indicating a warmer indoor environment compared to previous months. For May month, the results showed that the median PMV values for Case 1, Case 11, and Case 21 (one occupant) were −0.093, −0.176, and −0.088, respectively. In terms of PPD, these values were 5.2, 5.6, and 5.2%, as shown in Figure 14e. The maximum difference between all three cases was 0.4%. When comparing the CO_2 concentration as shown in Figure 15e, the results showed that Case 1 was below the recommended value of 1000 ppm. The median CO_2 results for Case 1, Case 11, and Case 21 were 940, 713, and 988 ppm, respectively. When comparing Case 1 in January vs. Case 1 in May, the decrease in CO_2 concentration is due to an increase in the ventilation flow rate because of the increased temperature indoors. This is shown in Figure 16e, where the median air supply flow rate results for Case 1, Case 11, and Case 21 were 3.63, 8.34, and 4.07 L/s, respectively.

When evaluating the month of June (Figure 13f), the results showed similar development as for May, with the difference being that the indoor climate was slightly warmer. As for the months of July and August, the results once again show a similar development for May and June, but a lower spread of PMV and also a slightly warmer indoor climate where the median PMV value is now above 0.

One special note can be taken for the July case (Figure 13g). For this month, the spread of PMV levels is very low between all the cases. The median PMV value of all the cases ranges between 0.1 and 0.2. This also means that the air supply flow rate for this month is very similar when comparing all the cases, as seen in Figure 16g. This, in turn, results in a very similar CO_2 concentration in the room when comparing this month to the other months in the year, as shown in Figure 15g. The median CO_2 concentration range is only ~300 ppm between all cases in this month.

In general, using only a temperature-controlled ventilation system results in a slightly better indoor climate from September-April. However, indoor air quality will become worse when using this type of control system. The overall best system to use is the combined temperature + CO_2 control system, where the CO_2 concentration and thermal comfort level are kept at an optimum level in combination with keeping a lower overall flow rate when compared to a system that is only CO_2 controlled. This result is in line with the finding by Asif & Zeeshan [9], which showed that if a room with occupants is not adequately ventilated, it can lead to the buildup of high concentrations of CO_2 within the space.

4.2. Results for Room 23:429

When evaluating the statistical values of PMV for Room 23:429 for January month (Figure 17a), the results showed that when one occupant was in the room, the different ventilation strategies performed very similarly, which was also the case for Room 23:425. The results showed that the median PMV values for Case 5, Case 15, and Case 25 were −0.562, −0.580, and −0.560, respectively. In terms of PPD, these values were 11.6, 12.1, and 11.6%, as shown in Figure 18a. The maximum difference between all three cases was 0.5%. When comparing the CO_2 concentration as shown in Figure 19a, the results showed that Case 5 was below the recommended value for 1000 ppm. The median CO_2 concentration results for Case 5, Case 15, and Case 25 were 895, 691, and 899 ppm, respectively. The maximum difference between Case 5 and 15 was 204 ppm (22.8%) which is significant.

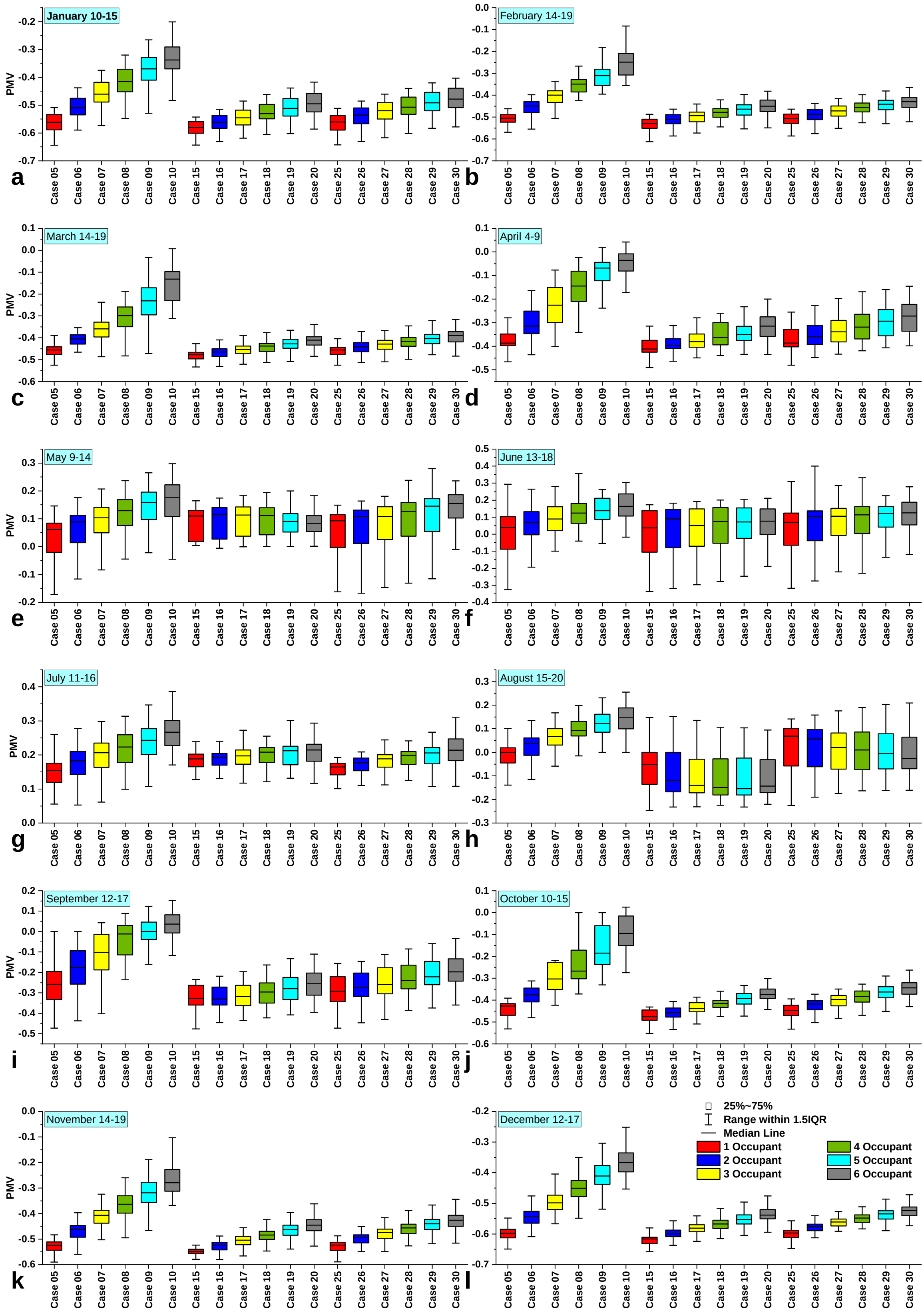

Figure 17. PMV evaluation for Room 23:429 with 1–6 occupants during various time periods.

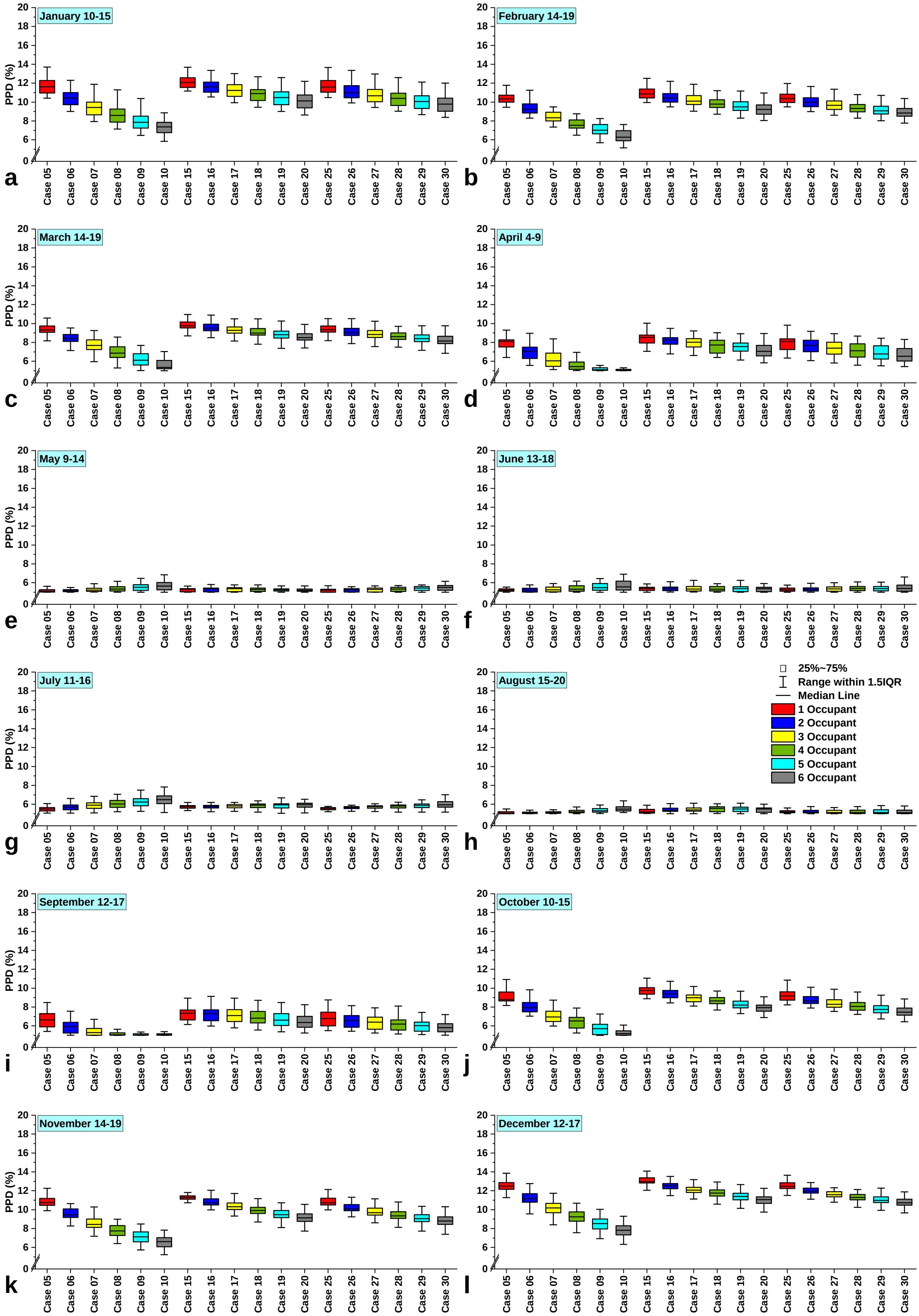

Figure 18. PPD evaluation for Room 23:429 with 1–6 occupants during various time periods.

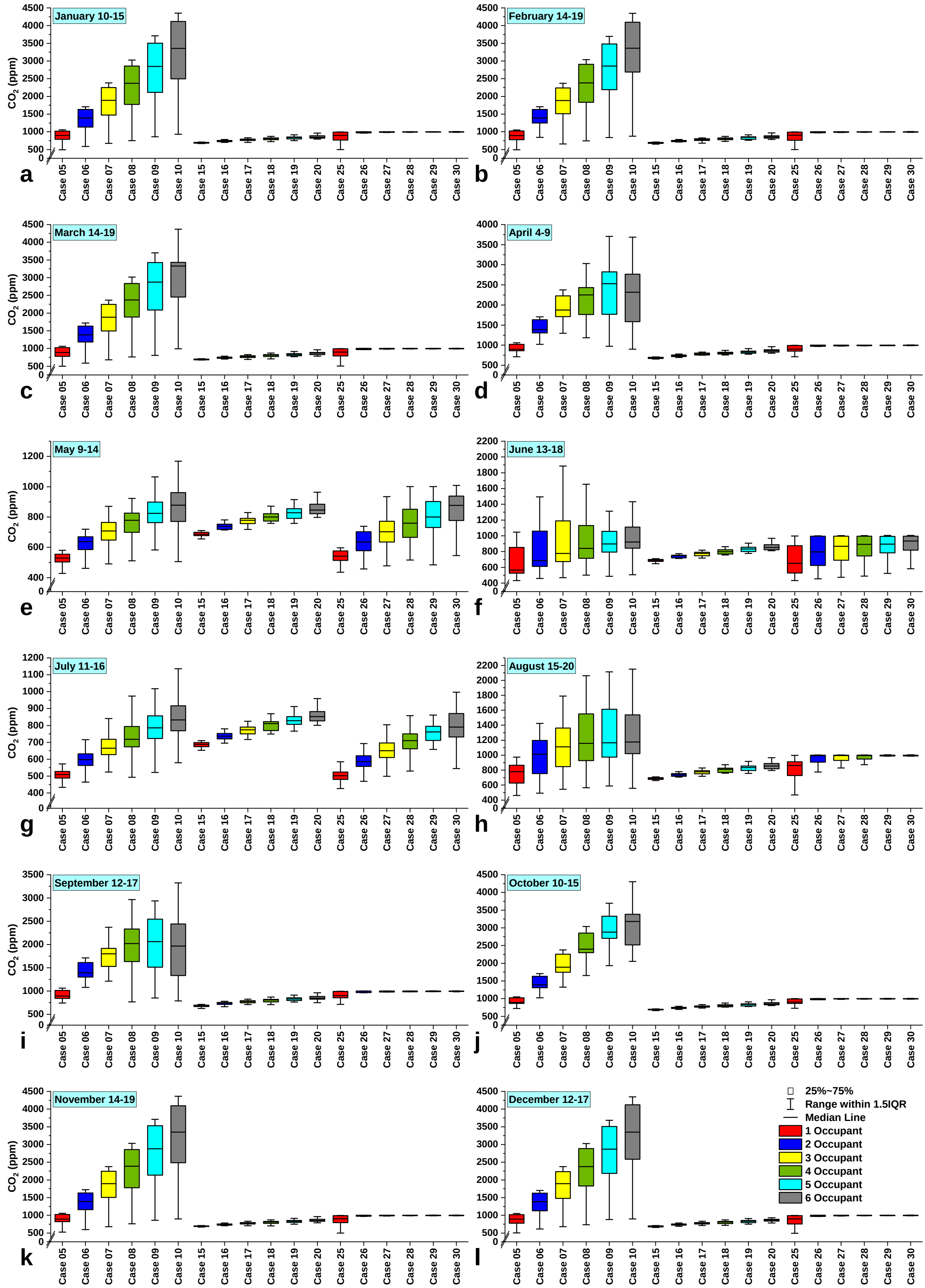

Figure 19. CO_2 evaluation for Room 23:429 with 1–6 occupants during various time periods.

When increasing the occupancy to two persons, the results showed slightly improved PMV values for all cases, as shown in Figure 17a. The results showed that the median PMV values for Case 6, Case 16, and Case 26 were −0.510, −0.562, and −0.536, respectively. In terms of PPD, these values were 10.4, 11.6, and 11.0%. The median CO_2 concentration for Case 6, Case 16, and Case 25 were 1387, 737, and 996 ppm, respectively. This showed that when increasing the occupancy to two or more, the ventilation that is only controlled by temperature does not respond adequately to improve the indoor air quality. As shown previously, this comes with the cost of an increased ventilation flow rate. When comparing Case 5 vs. Case 6 (e.g., 1 vs. 2 occupants), when only controlled by only the temperature, the ventilation flow rate does not change (4.15 vs. 4.15 L/s). However, when comparing Case 15 vs. Case 16, the ventilation flow rate is increased from 9.37 to 15.27 L/s when the ventilation system is CO_2 controlled and from 4.15 to 9.12 L/s (Case 25 and Case 26) when the ventilation system is temperature & CO_2 controlled. Further evaluation of the other Cases (Case 7–10, Case 17–20, and Case 27–30) showed similar behavior in that the systems with a CO_2 sensor increased the flow rate to reduce the CO_2 concentration in the room.

When looking at February, March, and April (Figure 17b–d), the results showed a similar development as for January month.

When looking at the warmer months of the year, May to August (Figure 18e–h), the results showed a median PPD value between 5 and 6% for all the cases. This is in contrast to the colder months (January to April and September to December). For example, when comparing May (Figure 18e) vs. January (Figure 18a), the PPD results showed a higher level of PPD for January, 11.75% vs. 5.2%. The PPD results (Figure 18e–h) are directly correlated to the PMV value for the same periods (Figure 17e–h). The results showed that for these months, the PMV values were much closer to the optimal neutral level of PMV 0 compared to the other colder months.

When evaluating the CO_2 results for the same period (May to August, Figure 19e–h), the results showed a significant reduction in the CO_2 concentration when compared to the colder months (January to April and September to December) for cases with increased occupancy, and that was supplied by temperature-controlled ventilation only. For example, when comparing May month, Case 10 (Figure 19e) vs. January month, Case 10 (Figure 19a), which has six occupants, the results showed a median CO_2 concentration of 870 ppm for May and 3300 ppm for January. This difference is due to the change in the ventilation flow rate, which can be seen in Figure 20. When evaluating the warmer months, May to August (Figure 20e–h) vs. the colder months (January to April and September to December, Figures 20a–d and 20i–l), the results showed that the ventilation system that is only controlled by temperature was only supplying the minimum required flow rate to the room.

In general, similar to Room 23:425, using only a temperature-controlled ventilation system results in a slightly better indoor climate during September-April. However, the indoor air quality will become worse when using this type of control system. The overall best system to use is the combined temperature + CO_2 control system, where the CO_2 concentration and thermal comfort level are kept at an optimum level in combination with keeping a lower overall flow rate when compared to a system that is only CO_2 controlled.

For future studies, it is worth investigating the co-optimization of both thermal comfort, indoor air quality, and also energy usage in terms of ventilation flow rate together with air supply temperature and humidity.

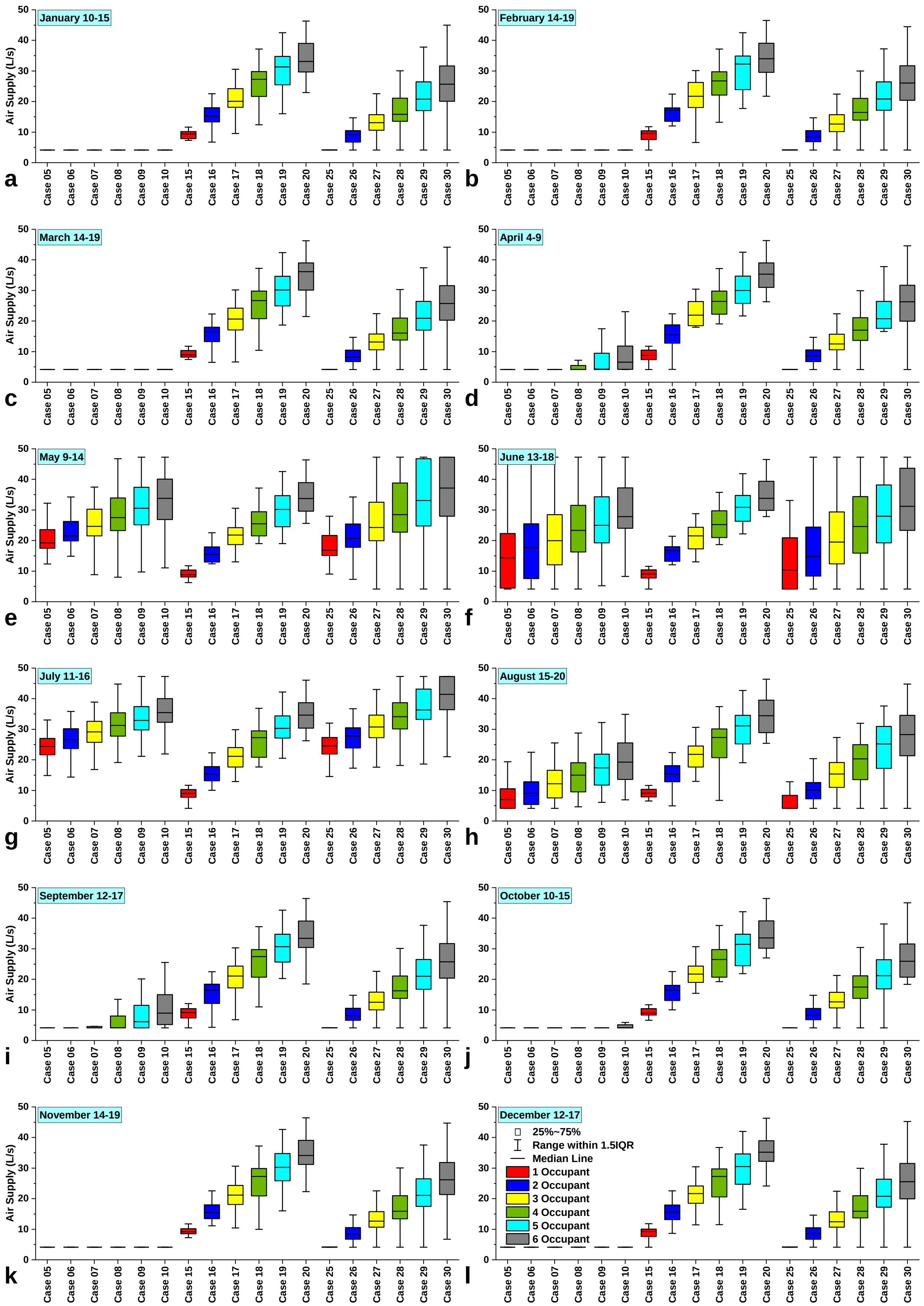

Figure 20. Air supply flow rate for Room 23:429 with 1–6 occupants during various time periods.

5. Conclusions

The results of the numerical studies showed that having more than one student in any of the rooms increased the CO_2 concentration above 1000 ppm when using the temperature-controlled ventilation system, which reduced the indoor air quality considerably. For this reason, even though the ventilation system provided an adequate level of thermal comfort, it can be concluded that the ventilation control should be changed to temperature + CO_2 controlled to fulfill both an adequate level of thermal comfort and good indoor air quality in terms of CO_2 concentration. However, as shown in the results, the temperature + CO_2 controlled system requires a higher ventilation flow rate, and this must be taken into account when changing the system in terms of more energy usage.

Author Contributions: Conceptualization, A.A., A.B. and I.E.A.; methodology, A.A., A.B. and I.E.A.; validation, A.A., A.B. and I.E.A.; formal analysis, A.A., A.B. and I.E.A.; investigation, A.A., A.B. and I.E.A.; resources, A.A., A.B. and I.E.A.; writing—original draft preparation, A.A. and A.B.; writing—review and editing, A.A. and A.B.; software, A.A. and I.E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CV(RSME)	coefficient of variation of the root-mean-square error
IAQ	indoor air quality
NMBE	normalized mean bias error (%)
PMV	predicted mean vote
PPD	predicted percentage dissatisfied (%)
VAV	variable air volume
VFR	ventilation flow rate [$L \cdot s^{-1}$]

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