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CO_2, temperature and RH in Swedish primary school classrooms with and without automatic window operation

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Abstract. Extensive field measurements have shown that school buildings ventilated naturally often suffer from insufficient air change rates (ACR) and elevated CO_2 concentrations, which can result in decreased alertness, lower school performance and increased absenteeism of children. Moreover, the variable character of natural ventilation can lead to unwanted fluctuations in thermal environment, which is highly dependent on the actual window operation conducted by the classroom staff, and outdoor weather conditions. Mechanical supply and exhaust ventilation systems, if designed and operated correctly, can provide sufficient ACR, and positively contribute to desired thermal conditions. However, their installation is not always possible due to various reasons. In such case, it is necessary to explore alternatives to ensure sufficient ventilation rates and acceptable thermal environment. This paper presents an analysis of continuous CO_2 concentration, temperature, and relative humidity (RH) measurements conducted in 45 Swedish primary school classrooms, equipped with different ventilation systems. The focus of the analysis is on the classrooms equipped with automatic window opening and mechanical exhaust ventilation. The measurements were performed during heating season and during one school week. Various statistical metrics were calculated, as well as the duration of periods when the investigated IEQ variables exceeded recommended value or were outside the recommended range. The variability of the thermal environment was also explored. All these results were compared with the remaining classrooms in the sample using different ventilation strategies. The classrooms with automatic window operation showed substantially lower CO_2 concentrations than the classrooms with manual window opening, regardless of whether these had natural ventilation or mechanical exhaust ventilation. The CO_2 concentrations were closer to the CAV/VAV classrooms. Temperature and RH were generally within acceptable ranges. Thus, the results suggest that automated window opening systems can improve the performance of natural and mechanical exhaust systems. The paper also addresses potential limitations and risks connected to such solutions.

1 Introduction

Nowadays, it is well described in the literature that poor indoor environmental quality (IEQ) in classrooms negatively affects pupils' health, well-being, and performance. Ventilation plays a key role in establishing good IEQ conditions indoors. However, the literature review by Fisk [1] has shown that reality is very often far from the desired state and the ventilation in classrooms is usually insufficient.

In Sweden, the majority of school buildings are ventilated by supply and exhaust mechanical ventilation systems [2]. Recent study has shown that classrooms in Swedish primary schools ventilated by balanced mechanical systems have higher air change rates and lower CO_2 concentrations than classrooms with untreated supply air [3]. However, the Swedish situation is quite unique compared to the other parts of Europe, where natural ventilation still prevails. SINPHONIE study documented the significant difference in indoor air quality (IAQ) among the European schools, stating that the majority (86%) of ventilation rates were lower than the desired value of 4 l/s.person [4].

Providing desired indoor conditions by the means of manual window opening can be a challenging task. The success of natural ventilation strategy relies on many factors, such as building design or actual outdoor weather conditions. Moreover, active occupant behaviour plays a key role in achieving desired IEQ, as it is usually occupants who are responsible for opening the windows. However, as Heracleous [5] has shown, the main motivation for window opening is not the air quality, but thermal discomfort. Therefore, higher ventilation rates are usually observed outside the heating season. The same was also concluded in a study conducted in schools in Central Italy. During the heating season, windows were usually opened less frequently and the CO_2 concentration often rose above the recommended levels [6].

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To achieve the desired IEQ in densely occupied spaces such as school classrooms, high ventilation rates are needed. Usually, it is not sufficient to ventilate the classroom only during breaks between lectures. On the other hand, frequent opening of windows and doors can result in unwanted draught leading to situations when occupants perceive thermal discomfort.

Balanced mechanical systems, when designed and operated properly, can provide sufficient ventilation rates and high IEQ. However, they cannot be installed in any school buildings due to various constraints, such as construction or economic. Another hinder could also be the building's historical value not allowing for any larger retrofit interventions. Therefore, it is important to find a well-functioning solution for those buildings, which still solely relies on opening of the windows.

Several studies have investigated the performance of classrooms using automatic window opening. Heebøll et al.[7] tested the suitability and performance of different ventilation retrofit solutions for a school building located in Denmark, one of them being an automatic window opening with mechanical exhaust. In this classroom, windows were open for 71% of the occupied period, resulting in significantly lower CO_2 concentrations than in a classroom with manual window opening. Temperature was within the recommended comfort range. The study also confirmed that the windows are rarely opened manually during heating season. The same study also concluded that visual CO_2 feedback display showing the actual CO_2 concentrations in the room is not a suitable solution as it did not lead to significantly lower CO_2 concentrations in a long term. Another study conducted in a school located in central Italy showed that the system of automatic window opening driven by the Humphrey's adaptive algorithm was able to provide CO_2 concentrations below 1500 ppm and thermal satisfaction of occupants [8] .

In Sweden, extensive measurements were done during the years 2019 and 2020 in 23 school buildings using different ventilation strategies. These measurements were used to analyse the differences in IEQ among classrooms using different ventilation strategies [3]. The results pointed out quite great ranges in IEQ indicators in classrooms ventilated with untreated air (manual or automatic window opening, or mechanical exhaust ventilation). This current study is using the same dataset and closely investigates the performance of the classrooms equipped with automatic window opening. CO_2 concentrations, temperatures and relative humidity values measured during one school week are compared to other classrooms included in the dataset using other ventilation strategies.

2 Methodology

2.1 Sample and measurements

The full sample, which is the same as in the previous study [3], includes 45 classrooms in 23 school buidlings located in Gothenburg, Sweden, which lies in warm and temperate climate (classified as Cfb as per Köppen-Geiger climate classification). The main selection criterium was the ventilation strategy in the classrooms. Table 1 provides an overview of the ventilation strategies used in the selected schools.

Table 1. Overview of the ventilation strategies used in the schools included in the sample.

Ventilation strategy	Description
Natural ventilation Manual window opening	Windows/doors are opened manually by occupants (usually teachers).
Mechanical exhaust ventilation Automatic window opening	Fresh air is supplied through windows which opened automatically with window actuators installed on the windows and operated by a system using specific algorithms. System is also supported by mechanical exhaust.
Mechanical exhaust ventilation Manual window opening	Air is supplied through windows, leakages, or vents, and exhausted using ventilation unit. No heat recovery.
Balanced mechanical system	Supply and exhaust ventilation system with constant air flow (CAV) or variable air flow (VAV). The heat from exhausted air is recovered and used for preheating of the supplied air.

Measurements were conducted during the heating season of the years 2019 and 2020. The duration was one week in each classroom (Monday to Friday). Air temperature, relative humidity and CO_2 concentration was measured using dataloggers Wöhler CDL 210 with two-minute intervals. Certain gaseous air pollutants and particulate matter concentrations were also measured, but they are not a subject of this study. More information about the schools, measurements and results can be found in [3].

Even though everyone could see on the display of the measurement equipment the actual levels of measured variables, no one was specifically instructed to react in any way based on the actual values.

The measurements were complemented with a survey conducted in each classroom in the middle of the measurement week. Children and teachers provided information about their thermal perception and preferences as well as opinion on the IEQ in the classroom. Additionally, teachers were also given an opportunity to share their opinions by answering a few open questions and provide a list of specific problems related to IEQ in the classrooms. In this paper, only the teachers' feedback is analysed. Future work will focus on the children's responses.

Most of the classrooms were occupied for 6 to 7 hours per day, starting at 8 a.m. and finishing between 2 or 3 p.m., with a few exceptions when the school day lasted little longer. The occupant density was ranging between 1.7 to 4 m^2/child, with a median value of 2.7.

Table 2 shows the number of classrooms in each ventilation group and some average characteristics. The classrooms in the sample have similar floor area, but their volume differs, which is caused by the different ceiling height. The uneven number of classrooms in the groups is caused by the fact that the original design of the study was different and the manual window opening, automatic window opening, and mechanical exhaust ventilation strategies were grouped together.

Table 2. Basic classroom characteristics

Ventilation strategy	Number of classrooms in the analysis	Average classroom volume [m²]	Average floor area [m²]
Natural ventilation Manual window opening	4	206	59
Mechanical exhaust Automatic window opening	3	195	60
Mechanical exhaust Manual window opening	6	188	53
CAV	15	176	59
VAV	16	157	54

2.2 Automatic window opening

Four classrooms in two schools were equipped with automatic window opening systems. As the two schools use different control and operation systems for the automatic window opening, they are treated separately in the analysis.

2.2.1 School 1

School 1 is located close to the city centre, but not close to any heavy traffic road. It was built in 1893, and has been subject to some minor renovations, including the installation of automatic window opening and external awnings.

The exhaust fan is running weekdays between 6 am and 5 pm. During this period a motorized mechanism controls the window opening with respect to room temperature and CO_2-concentration. The windows are closed when the temperature and CO_2-concentration are below 22°C and 700 ppm, respectively. When the temperature increases above 22°C the window opening increases. The most open position is reached when the temperature reaches 24°C. A corresponding function increases the window opening when the CO_2-concentration increases. The most open position is reached at 1000 ppm.

Occupants of the room can override the automatic control to keep the windows closed for a period selectable between 15 and 60 minutes. After that, the windows are automatically controlled again.

The two classrooms in this school will be further referred as S1C1 and S1C2.

2.2.2 School 2

School 2 is located at the outskirts of the city, but close (less than 200 m) to a highway. The classrooms' windows are south-east oriented and face towards low-traffic street.

The school, built in 1950, was originally equipped with mechanical exhaust air. It was subsequently complemented with a system for automatic window opening. Thus, air is supplied through windows equipped with motors allowing for automatic opening, or through leakages and vents when windows are closed, and exhausted through mechanical system. The system is controlled with respect to the room temperature, VOC concentration and presence of occupants in the room.

Occupants of the room can override the automatic system and keep the window opened for 30 minutes. After that, the windows close automatically again.

Measurements were originally done in two classrooms, however, one of them was used as a classroom for individual support and the occupant density was much lower, which was reflected in the result. Therefore, this classroom was excluded from the statistical analysis, but included in the figures.

The classroom in this school that was statistically analysed will be further referred as S2C1.

2.3 Other ventilation strategies

Four classrooms in two schools were ventilated only by manual window opening. It is usually the classroom staff (teachers) who are responsible for the window opening.

Six classrooms in three schools were equipped with mechanical exhaust systems. It was possible to manually open the windows in these classrooms.

In total 31 classrooms, which constituted 2/3 of the sample, were equipped with balanced mechanical ventilation systems, either with constant air volume or variable air volume with or without demand control.

3 Results

In this section, the CO_2 concentration, temperature, and RH in the three classrooms equipped with automatic window opening are compared with the median values of different statistical metrics in other ventilation categories. The three classrooms with automatic window opening are further referred as "investigated classrooms".

The investigated classrooms are treated separately, as the control and operation system differ among the two schools.

Only the values measured during occupied times in respective school were considered in the statistical analysis. In each section, the medians of average values, 95^{th}-percentiles and IQR were summarized. The value of 95^{th}- percentiles better illustrates the conditions after each class, while IQR illustrates the variability of the indicator. Also, the percentage of time when the indicator is outside recommended range (temperature and RH) or exceeds the recommended value (CO_2) was calculated for each ventilation strategy group and the investigated classrooms.

3.1 CO_2 concentration

Table 3 summarizes mean values of CO_2 concentration, 95th-percentiles and IQR during occupancy.

Table 3. Mean values of selected statistical metrics for CO_2 in different ventilation groups.

Ventilation strategy	CO_2 mean	CO_2 95th-%	CO_2 IQR
Natural ventilation Manual WO	1498	2228	590
Mechanical exhaust Manual WO	1140	2047	719
CAV	661	900	302
VAV	640	841	240
S1C1	808	1347	287
S1C2	779	1017	268
S2C1	895	1618	363

CO_2 averages and 95th percentiles in both school 1 and 2 are slightly higher than in schools equipped with balanced mechanical systems, but they are lower than in schools using manual window opening or exhaust ventilation. The values of IQR are close to those in CAV/VAV groups, indicating smaller variations during the occupancy compared to strategies with manual window opening. The difference between the classrooms in school 1 was caused mostly due to higher CO_2 levels during Monday. The concentrations during the remaining days of the measurement week were similar in both classrooms (see Fig. 1).

Figures 1 and 2 show the CO_2 concentration during a 3-day period (Tuesday – Thursday) in the investigated classrooms. Highlighted areas correspond to occupied times in the classrooms.

Figure 3 shows a typical CO_2 curve for a classroom equipped with a VAV system. The pattern is similar to the one seen in Fig. 1, but the peaks in Fig. 3 are lower, typically below 750 ppm.

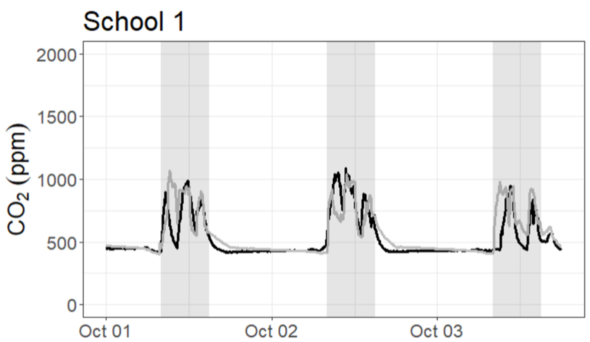

Fig. 1. CO_2 concentrations in the two classrooms of school 1.

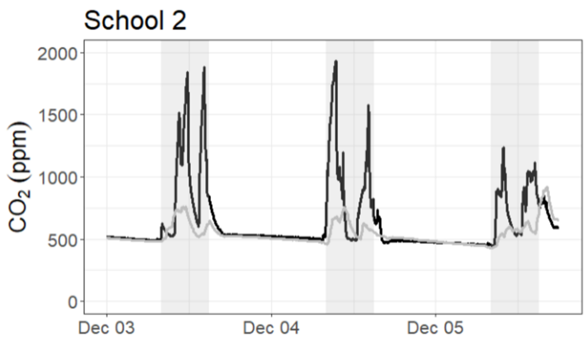

Fig. 2. CO_2 concentration in the two classrooms of school 2.

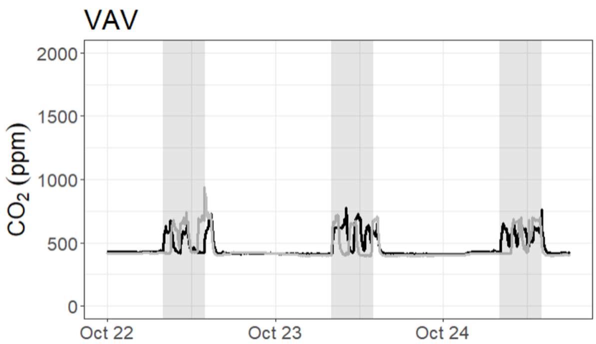

Fig. 3. CO_2 concentration in two classrooms of a school with VAV system.

Table 4 shows the percentage of occupied time with concentration of CO_2 above 1000 ppm. The percentage for each ventilation strategy group was calculated as the total number of hours outside the range divided by total number of occupied hours for all classrooms in each ventilation group.

As Table 4 indicates, in case of balanced mechanical systems (CAV and VAV), the CO_2 concentration rarely exceeds this threshold. The values for investigated classrooms are closer to mechanical ventilation systems, however, there are differences among all three investigated classrooms. The higher value in S1C1 is caused mostly by higher CO_2 value on Monday compared to the remaining days. In school 2, the values of CO_2 were generally higher than in school 1 during the whole measurement week.

Table 4. Percentage of occupied time with CO_2 above 1000 ppm.

Ventilation strategy	Percentage of occupied time with CO_2 above 1000 ppm
Natural ventilation Manual WO	85%
Mechanical exhaust Manual WO	52%
CAV	3%
VAV	1%
S1C1	17%
S1C2	7%
S2C1	28%

3.2 Temperature

Table 5 summarizes mean values of temperature, 95th-percentiles and IQR during occupancy.

Table 5. Mean values of selected statistical metrics for temperature in different ventilation groups.

Ventilation strategy	Temp mean	Temp 95th-%	Temp IQR
Natural ventilation Manual WO	21.4	22.9	1.19
Mechanical exhaust Manual WO	22.1	23.4	1.27
CAV	21.1	22.0	0.88
VAV	21.1	21.7	0.60
S1C1	21.4	22.6	1.10
S1C2	21.5	22.1	0.50
S2C1	21.0	22.1	0.80

The values of all statistical metrics for the investigated classrooms lie approximately between the values for mechanically ventilated buildings and those using manual window opening. Generally, they are slightly higher than for CAV/VAV groups, but slightly lower than for the manual window opening groups.

Table 6 shows the percentage of occupied time when the temperature was outside the range of 20 – 24ºC as recommended by Swedish Work Environment Authority [9]. The values were calculated in the same way as in Table 3 for CO_2 concentrations.

Table 6. Percentage of occupied time with temperature outside the recommended range 20 – 24 ºC.

Ventilation strategy	Percentage of occupied time outside the temperature range (20 – 24ºC)
Natural ventilation Manual WO	12%
Mechanical exhaust Manual WO	30%
CAV	24%
VAV	11%
S1C1	3%
S1C2	1%
S2C1	0%

In this case, the performance of investigated classrooms is much better compared to all other categories. However, it is important to point out that in both CAV and VAV group, there were classrooms with temperatures being within this interval all the time, but also classrooms with the temperature being outside the interval for majority of the occupied period, which has influenced the total percentage given in the table. On the other hand, in the group relying on window opening or mechanic exhaust, there were no classrooms where the temperature was within this range all the time. Thus, the performance of investigated classrooms is similar to the best performing CAV/VAV classrooms.

Figure 4 and 5 shows the temperature during 3 days in the investigated classrooms. There is an interesting difference in temperature trend during and outside occupancy. In school 1, the temperatures are more stable during the whole measurement period, while in school 2, the temperature peaks clearly indicates when the room was occupied.

Figure 6 shows the temperature in a school equipped with VAV system (same school as in Figure 3). Even though the temperature during occupancy is within the recommended range, the temperature outside occupied hours is quite high, which is not positive especially from an energy use point of view. This emphasizes the need for correct control and operation of the whole system to achieve both required IEQ and low energy consumption.

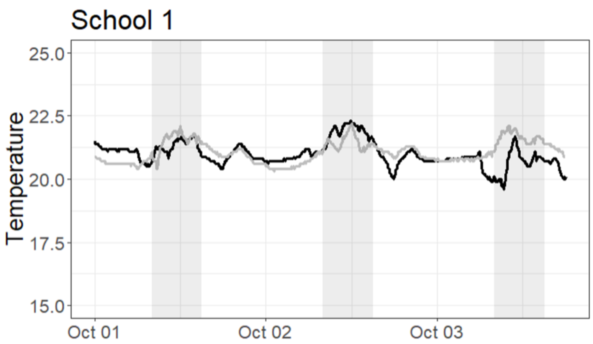

Fig. 4. Temperature in classrooms of school 1.

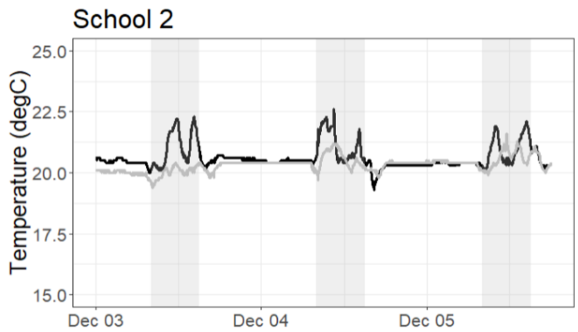

Fig. 5. Temperature in classrooms of school 2.

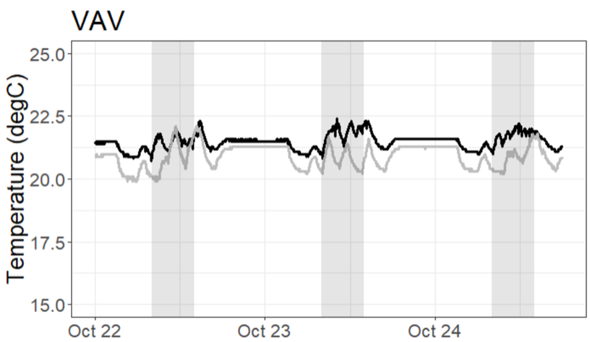

Fig. 6. Temperature in two classrooms in school with VAV system.

3.3 Relative humidity

The values of RH were analysed in a similar was as in the CO_2 concentrations and temperature. However, the value of indoor RH is very much dependent on the outdoor conditions, especially on the outdoor temperature. It is common to observe lower RH indoors during heating season when the outdoor temperature drops. Even though all the measurements were conducted during heating season, they were not done simultaneously. The weather conditions during each measurement week were different and this influenced the measured values of indoor RH. Therefore, the conditions in the schools should be compared carefully.

Table 7 summarizes the calculated statistical metrics for RH during occupied time. Similarly, as for the temperature, the RH values in investigates classrooms were between the values in mechanically ventilated classrooms and those using manual window opening, though 95th-percentiles in school 1 were somewhat higher. RH in school 2 was lower than in school 2, but this might be caused by the difference in outdoor temperatures during the measurement week (see Figure 7 and 8).

The results also indicate the difference between CAV and VAV systems and the remaining ventilation strategies. However, it is important to note that these classrooms were ventilated with much higher ventilation rates than classrooms using different strategies, which has also an effect on RH values.

Table 7. Mean values of selected statistical metrics for RH in different ventilation groups.

Ventilation strategy	RH mean	RH 95th-%	RH IQR
Natural ventilation Manual WO	40	48	6.49
Mechanical exhaust Manual WO	38	45	5.55
CAV	32	40	8.06
VAV	35	41	6.81
S1C1	36	52	3.75
S1C2	41	55	4.00
S2C1	35	44	10

Table 8 shows the percentage of time when RH was outside the range of 30 – 60%. This is a range recommended for schools by US Environmental Protection Agency [10]. In most of the cases, when the RH was outside the range, it was lower than recommended, with an only exception of school with manual window opening and exhaust system, when the value was higher than 60%.

Table 8. Percentage of occupied time with RH outside the range 30 – 60%.

Ventilation strategy	Percentage of occupied time outside the RH range (30 – 60%)
Natural ventilation Manual WO	10%
Mechanical exhaust Manual WO	39%
CAV	35%
VAV	27%
S1C1	10%
S1C2	0%
S2C1	24%

The results from table 8 confirms the general issue with low RH during heating season.

Figures 7 and 8 depict the RH in the investigated classrooms. The dashed curve shows the corresponding outdoor temperature.

The outdoor temperature during the measurement week in school 1 was quite stable, but in school 2, there was an increase in outdoor temperature after the first day, which is apparent at the beginning of the curve. The value of indoor RH reacted on this by slight increase.

For comparison, Figure 9 illustrates RH in a school with VAV system (same school as Figure 3 and 6).

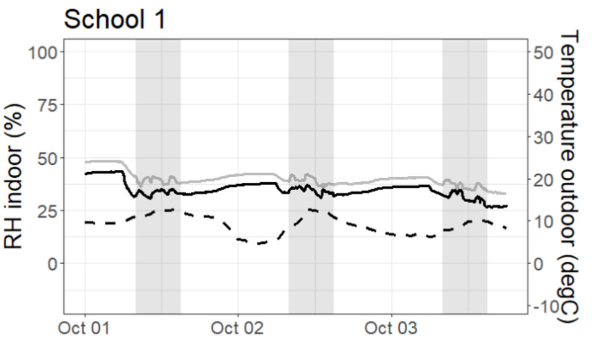

Fig. 7. RH in the two classrooms of school 1. Dashed line represents the outdoor temperature.

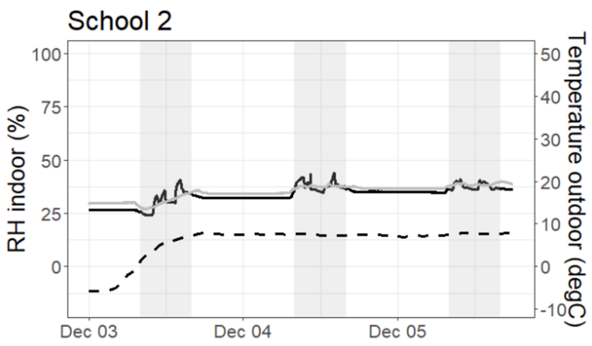

Fig. 8. RH in the two classrooms of school 2. Dashed line represents the outdoor temperature.

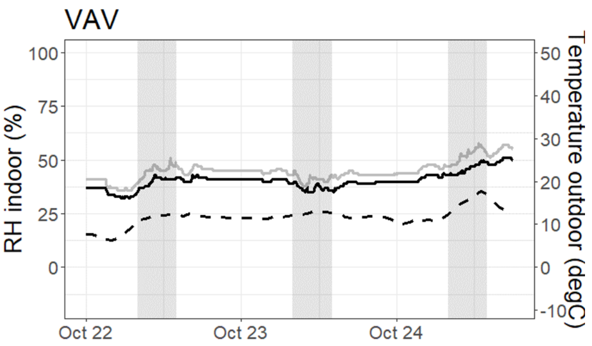

Fig. 9. RH in the two classrooms of school with VAV system. Dashed line represents the outdoor temperature.

4 Discussion

The comparison of investigated classrooms with other ventilation strategies suggests that these classrooms usually stand somewhere between the manual window opening and balanced mechanical systems. It seems that if the system is well controlled and operated, the CO_2 concentrations can be within reasonable ranges, and lower than in classrooms with manual window opening.

The investigated IEQ conditions in both classrooms of school 1 were quite similar, except for a few peaks of higher CO_2 concentration on the first measurement day resulting in slightly higher 95th-percentile value.

However, the CO_2 concentrations in school 2 were consistently higher during the measurement week than in school 1, with peak values exceeding 1500 ppm. This can be caused by the different control strategy used.

4.1 Teachers' opinion on IEQ

During the measurement campaign, teachers in the classrooms (one per classroom) were asked to participate and provide their view on the IEQ. Thanks to this, some additional views on classrooms' IEQ and function of the ventilation system were obtained.

According to the survey and interview with the teachers teaching in the investigated classrooms, excessive noise was one of the most frequent complaints. The noise comes both from the outside, when windows or doors are opened, and from the operation of window actuators. The noise from the actuators can be especially disturbing when windows are opening and closing frequently. Teacher in school 2 confirmed that when the pupils need to focus, she uses the option to override the automatic mechanism and keep the window opened for 30 minutes. The same teacher also mentioned that they sometimes experience difficulties with opening the door when the windows are closed. This is probably due to under-pressure caused by the exhaust system and missing or malfunctioning vents.

The input from the survey also showed the problems with the perception of cold and draught, especially close to the windows, pointing to problems with local thermal discomfort. All the teachers also confirmed that they or someone else had handed in complaints about the IEQ in the classroom.

Supply of untreated, especially non-preheated air during winter in building requiring high ventilation rates may be problematic, leading to either thermal discomfort issues or poor indoor air quality. As Ekberg and Abel described [11], a newly built primary school building located in Sweden and formerly equipped with automatic window opening had to be completely rebuilt due to massive complaints on IEQ resulting in health issues of both teachers and pupils. The most frequent complaints were on stale and stuffy air, cold and draughty indoor air, and noise from outdoor. Due to discomfort problems, teachers were closing the windows manually, which resulted in low ventilation rates and poor IAQ. As there was no other suitable solution, the building had to be evacuated and additionally equipped with balanced mechanical ventilation system. The final price for the school remediation was extremely high and points out to the need of proper and careful design.

4.2 Limitations

The measurements could not be done during the same week in all the school buildings. Even though they were all conducted during the heating period, when the outdoor temperature is lower than indoor temperature, the measurement campaign stretched over several months with different weather conditions. Especially in classroom ventilated by manual window opening, the outdoor conditions can play an important role in motivation of the occupants to open the window. Their behaviour can significantly affect the indoor conditions. Outdoor conditions also largely influence the values of RH indoors, as mentioned in the respective chapter.

The measurements were not done during the non-heating period. However, research suggests that the CO_2 concentrations are usually lower during non-heating period compared to heating period as the occupants tend to open the windows more often.

Due to the small size of the sample, the results cannot be generalized to all similar schools.

5 Conclusion

This study focused on analysing the performance of three classrooms in two different schools equipped with automatic window opening and exhaust system. The values of CO_2, temperature and RH were compared to the performance of other classrooms using different ventilation strategies, such as manual window opening with or without mechanical exhaust ventilation, and balanced mechanical ventilation systems with CAV or VAV.

Generally, the systems with automatic window opening performed better than classrooms relying on manual window opening. The concentrations of CO_2 were much lower and were also closer to concentrations measured in classrooms ventilated by CAV or VAV systems. The temperature was also within the required range of 20 – 24°C. RH was different in all three analysed classrooms,

Even though both of the investigated schools were equipped with the automatic window opening system with mechanical exhaust, the performance was different, as their control and operation system was different.

However, even though the measurements showed some promising results, the survey among teachers confirmed several potential problems and issues, such as excessive noise and thermal discomfort issues. This might lead to user-induced actions, such as blocking the automatic mechanism, resulting in poor IAQ.

Further investigation of the system performance in different seasons of the year as well as measurements focusing on local thermal comfort would be beneficial to complement the understanding and to provide appropriate design solutions and suggestions.

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