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Effect of demand-controlled ventilation strategies on indoor air pollutants in a classroom: A Norwegian case study

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Abstract. The choice of the minimum ventilation rate (V_{min}) in a demand-controlled ventilation strategy can influence energy demand but also introduce outdoor air pollutants. The latter may have direct health effects, as well as affect indoor chemical reactions. In this paper, we evaluate the effect of ventilation rates and operation hours on the level of CO_2, nitrogen dioxide (NO_2), and ozone (O_3) in a classroom during normal use. We compared the baseline ventilation scenario (S0) with a V_{min} of 430 m^3/h with S1; V_{min} of 150 m^3/h for normal ventilation operation time (6:30-17:00) and continuous ventilation for 24h (S2). We found that S1 with reduced V_{min} would lower the ozone concentration by 35% during the hours before occupancy compared to S0. Moreover, continuous ventilation during night time with a low V_{min} resulted in almost as high O_3 concentrations as the baseline ventilation scenario. As O_3 reacts easily with certain VOCs to produce secondary organic aerosols, the level of V_{min} and the ventilation duration would impact the indoor air quality upon entering the classroom.

1. Introduction

For buildings with varying occupancy or pollution load, especially in offices and schools where rooms are unoccupied for most of the operational time, demand-controlled ventilation (DCV) can significantly improve energy performance compared to constant air volume (CAV) ventilation [1–3]. Seppänen [4] summarized how different (ventilation) strategies could reduce energy consumption and improve indoor air quality. Among them is demand-controlled ventilation, which may enhance air quality and yield up to a 50% reduction in energy usage for large spaces. Thus, efforts have been made to design DCV systems that provide recommendable air quality with little input in energy consumption.

The ventilation airflow rate in modern DCV systems is controlled between the predefined minimum (V_{min}) and maximum (V_{max}) limit values, based on the signal from one or more room sensors, typically CO_2 and/or measured air temperature. The V_{min} and V_{max} limit values are set to account for, for example, pollutant load from materials, room size, or the maximum pollutant load from occupants. The choice of V_{min} has an obvious impact on energy use, but there are few studies on the impact on indoor air quality (IAQ) [5–7]. Previous studies performed in unoccupied classrooms have shown no significant effect on perceived air quality (PAQ) by increasing V_{min} above 1.0 $l/s/m^2$ for classrooms with no additional pollutant sources [6,7].

A possible rationale for choosing the ventilation rate is to maintain a constant IAQ based on sensory pollution strength (olf) suggested by Fanger [8]. This implies that V_{min} is set to achieve an acceptable olfactory level accounting for the total pollutant load from materials and that ventilation is increased above V_{min} according to pollutants from occupants in the room. For unoccupied rooms, the minimum ventilation demand varies typically from 0.7 to over 2.0 l/s/m² in Norway. V_{min} is often set to the upper end of this range due to the risk of high-emitting furniture. While this strategy may be a robust choice to account for unexpected pollutant sources, it increases energy demand and introduces outdoor pollutants at a higher rate. Some of these may have direct health effects, as well as affect indoor chemical reactions [9,10].

The objective of the study was to examine the interplay between ventilation strategy and outdoor as well as stationary and transient indoor pollutant sources. In this paper, we evaluate the effect of ventilation rates and operation hours on the level of CO_2 concentration, nitrogen dioxide (NO_2), and ozone (O_3) in a classroom during normal use by 6-7-year-old pupils.

2. Methods

2.1. Study design

The measurements took place in a classroom at a primary school located 500 m southwest of a highway north of central Oslo, Norway. The three-story school building was completed in August 2016 after the Norwegian passive house standard [11]. The classrooms are similar in size, with an average floor area of 60 m^2 (59.7) and a height of 2.8 m, and have similar furnishings. The selected classroom is situated on the second floor and is occupied by first graders (aged 6-7 years).

A full class consisted of 24 pupils and two teachers. The first graders had no fixed daily schedules. Oftentimes the class would be divided into groups, so the classroom was frequently not fully occupied. A typical school day started at 8:30 and finished at approximately 14:45. The teaching sessions with a full class were few and varied in time and duration. Most of the time, the pupils were either outside playing or split into groups to participate in various activities in other classrooms. Nevertheless, there were two eating breaks daily when the entire class was gathered, one at 10:30 and one at 14:15. Due to the high frequency of change in pupils during classroom time, security and GDPR, automatic occupancy detection (e.g., sensor counters, cameras or survey) with ground truth were not established but was performed manually.

The school has balanced supply and exhaust mechanical ventilation with a cooling battery, rotary heat exchanger, and water heating battery. If there is a cooling demand for supply air and a lower extract temperature than the outdoor temperature, the heat recovery unit will act as a cooling recovery unit. The ventilation airflow rates in all classrooms were demand-controlled by CO_2- and temperature signals from a room sensor. When CO_2 exceeds 500 ppm and/or room temperature exceeds 23 °C, ventilation rates are increased above V_{min} by opening dampers. An optimizer system adjusts the fan power to achieve demanded airflow rates with as low duct pressure as possible [12].

The ventilation system had glass fiber bag filters of class F7 type Standard-Flo XLT 7 with a minimum efficiency of 41% for particles <1µm diameter, but no carbon filtering to reduce gaseous compounds. The bag filters were replaced in July 2017. The normal ventilation operation time was between 6:00 – 17:00 during the weekdays, and the ventilation was turned off during the weekend.

Table 1. Overview of the three ventilation scenarios for the weekdays.

	Ventilation operation time	**V_{min} (m³/h)/(l/s/m²)**	**V_{max} (m³/h)**	**CO_2 setpoint (ppm)**	**Temperature setpoint (°C)**
Baseline S0	06:30-17:00	430 / 2.0	1060	500	25
S1	06:30-17:00	150 / 0.7	1060	1000	25
S2	00:00-24:00	150 / 0.7	1060	1000	25

An overview of the three ventilation scenarios and the relevant setpoints is shown in Table 1. For the three-week-long measurement campaign, between 28 May and 18 June 2018, the ventilation operation time was manually adjusted to 6:30 – 17:00 during weekdays and 8:00 – 17:00 during weekends. The ventilation was turned off during the third weekend. As the measurement campaign took place during the year's warmest month, a higher temperature setpoint was chosen to prevent the ventilation system from operating with maximum airflow during unoccupied hours. Due to time constraints and the availability of the study site, it was not possible to repeat the measurement campaign for other periods.

The concentration of ozone (O_3) in the classroom was monitored using a UV absorption analyzer (Thermo Model 49C O_3 Analyzer). Nitrogen oxides (NOx, consisting of NO_2 and NO) were measured in the classroom using a chemiluminescence analyzer (Teledyne API 200A). Both parameters were logged with a 1-minute time resolution. O_3 was also measured in the supply air every 15th minutes.

The building management system (Desigo CC, Siemens Switzerland Ltd) provided measurement data on carbon dioxide (CO_2), temperature, and ventilation airflow rates. Log data from the building management system (BMS) is event-based, meaning a value is only provided if there is a change from the previous value. For comparison purposes, we also placed two Rotronic CP 11 (Rotronic AG, Bassersdorf, Switzerland) on top of a cupboard inside the classroom, approximately 30 cm above the room sensor, to log room temperature, relative humidity (RH), and CO_2 concentration with a 1-minute and 5-minute time resolution. Three Tinytag Plus 2 (Gemini Data Loggers, UK) were placed in different locations in the classroom; next to the Rotronics, in the extract air duct, and on the windowsill. These were also logged at 5-minute intervals. In addition, hourly mean weather statistics including outdoor air temperature and RH were also collected from the local weather monitoring station (via seklima.met.no, Norwegian Centre for climate services). Advanced measurements of volatile organic compounds (VOCs) and size and number concentration of particles with diameters from 10nm to 350 nm were also performed, but not analysed in this paper. The sampling campaign with an overview of the different ventilation scenarios is shown in Table 2. The different ventilation scenarios were manually adjusted by changing the setpoints in the centralized BMS, while the airflow rates (V_{min}) were adjusted using a handheld ZTH (Belimo) that connects directly to the VAV-controller.

Table 2. Overview of the different ventilation scenarios during the sampling campaign.

Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
22	S0	S0	S1	S1	S1	S1	S0
23	S2	S2	S0	S0	S0	S1	S0
24	S1	S1	S2	S2	S2	Off	Off

2.2. *Data processing, cleaning, and analysis*

The data from the measurement campaign was treated in Python 3.8/Spyder. The data cleaning consisted of the following steps; calculating missing data, removing Not-a-Numbers (NaNs), resampling the timestamp, and interpolating. As earlier mentioned, O_3 and NO_2 sampled instantaneous values every 1 minute. The CO_2 concentration, air temperature, relative humidity, and ventilation air flow rate) samples data based on instantaneous event changes down to 1-minute (event-based sampling) with individual timestamps. The event-based sampling occurred up to 30 times per hour for the NO_2 and O_3 concentrations, and as low as five times per hour. The CO_2 concentration, air temperature (T), and RH were sampled approximately 8-12 times per hour. Moreover, as mentioned earlier, the ventilation air flow rate is controlled to modulate between a predefined V_{min} and V_{max}, resulting in fewer sampled data points, thus resulting in an uneven timestamp for the entire data set. The resampling was performed every 5th minute, meaning averaging each parameter every five minutes. Some minor technical difficulties occurred during the measurement campaign (e.g., unplugging the equipment and electricity breakout at the school), resulting in missing data. The high frequency of event-based sampling and resampling of the data set naturally induced some NaNs, thus linear interpolation was performed.

To find the most representative measurement of the room parameters CO_2, room temperature, and relative humidity, we performed correlation analysis using Spearman's rank correlation coefficient (r_s) of the available measurements from the different loggers. It was decided to use the average value of the measurements for further analysis. High correlations were found for all three parameters; air temperature

($r_s > 0.9$), CO_2 concentration (rs=0.62 - 0.95, lowest was found for the logger placed at the window sill), and RH ($r_s > 0.98$).

Violin plots were used to compare the distribution of the measurements for the different ventilation scenarios. A violin plot summarizes a data set using a boxplot to show the minimum, 1st quartile, median, 3^{r}d quartile, and maximum and a probability density function (PDF) to show the shape of the data set. The width of the PDF indicates the frequency at which the value occurs.

3. Results and discussion

In the following section, when concentration ranges are described, they refer to concentrations inside the classroom unless otherwise stated.

3.1. Measurement campaign results

The measured air temperature inside the classroom was relatively stable during the sampling period (weekends omitted), with daily average temperatures ranging from 22.3 ºC to 23.9 ºC. The highest air temperature was measured on May 30th (25.6 ºC), where the outdoor temperature was 30.5 ºC. Relative humidity (RH) indoors fluctuated more, with daily average values between 24.1% and 49.9%, which is lower than anticipated. During the measurement period, it was unusually sunny with relatively low daytime outdoor relative humidity (average daily RH between 35% - 83.7%). The average daily CO_2 concentrations varied between 460 ppm – 645 ppm, with peak concentrations between 592 ppm and 1355 ppm.

The daily average NO_2 concentration varied between 2.2 and 11.8 μg/m^3, with daily peak concentrations of 3.3 – 37.5 μg/m^3, which are well below the WHO recommended guidelines for indoor air of 200 μg/m^3 (1-hour mean) [13]. The air quality guidelines (AQG) for short-term exposure to NO_2 were updated in 2021 and recommend a level of 25 μg/m^3 (24-h average allowing 3 – 4 exceedance days per year)[14]. The daily average O_3 concentrations varied between 8.2 and 24.9 ppb (~16.5 – 49.7 μg/m^3), with peak concentrations of 16.9 – 47.1 ppb (~33.8 – 95.2 μg/m^3). The recommended short-term daily maximum AQG level for ozone is set to 100 μg/m^3 (8-h average, allowing 3-4 exceedance days per year). A comparison of the daily average O_3 concentrations in the supply air and indoors resulted in indoor-outdoor (I/O) ratios between 0.43 – 1.02. Due to the unusually hot sunny weather during the measurement campaign, the ozone concentrations were higher than usual in Oslo during summer.

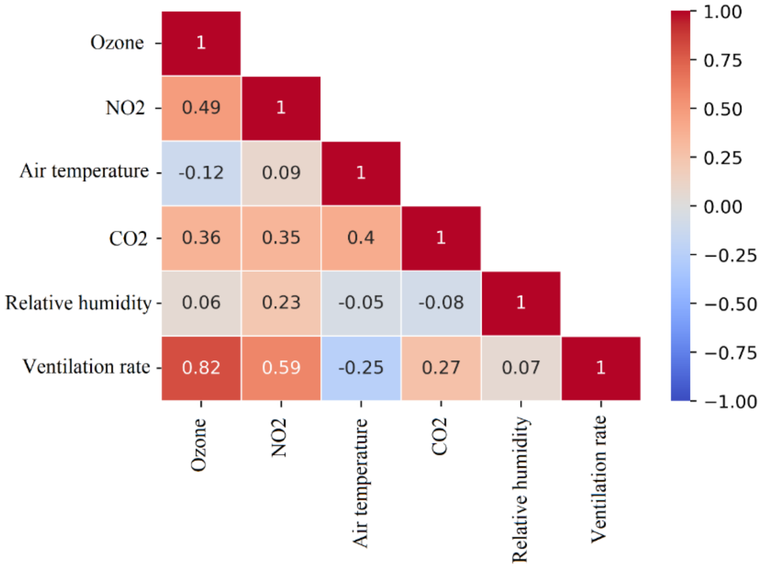

Figure 1. Correlation plot of the measured parameters, Spearman's ranked correlation.

In the absence of indoor sources, indoor O_3 concentrations are estimated to be 30-70% of outdoor levels, depending on the air exchange rate, ozone removal rate, and the reactions of ozone with other chemical compounds [10,15]. O_3 greatly impacts indoor air pollutants, as it can react with certain volatile organic compounds (VOCs), and the products of these reactions may be of higher concern than the VOCs themselves [9,16]. As seen in Figure 1, we found a moderate to high correlation between NO_2 (Spearman's ranked r_s=0.49) and O_3 (Spearman's ranked r_s=0.82) with the supply airflow rate. Our findings support the notion that indoor O_3 varies with the ventilation rate.

3.2. Measured concentrations during occupied hours

To prevent the DCV-system from operating with maximum airflow rates during the day (unoccupied hours), we adjusted the temperature setpoint to 25 °C. Table 3 shows descriptive statistics during the hours the classroom was assumed occupied.

Table 3. Descriptive statistics of the various indoor parameter during occupied hours (8:30 – 15:00).

Parameter	Scenario	Mean	Standard deviation	Median	Minimum	Maximum
O_3 [ppb]	S0	25	6	24	12	44
	S1	20	7	19	7	38
	S2	15	6	15	6	30
NO_2 [µg/m^3]	S0	14	5	13	6	37
	S1	12	5	11	4	30
	S2	9	5	10	2	26
CO_2 [ppm]	S0	575	76	574	430	747
	S1	759	179	756	419	1356
	S2	768	158	781	412	1253
Supply airflow rate [m^3/h]	S0	936	166	1024	429	1077
	S1	214	143	150	137	1062
	S2	180	87	150	138	914
T (room) [°C]	S0	22.4	0.4	22.4	21.7	23.8
	S1	24.2	0.5	24.1	23.1	25.6
	S2	23.3	0.6	23.4	21.1	24.3
T (extract air) [°C]	S0	22.4	0.6	22.4	21.2	23.7
	S1	24.5	0.8	24.4	22.7	26.9
	S2	23.6	0.9	23.7	20.7	25.4
RH (room) [%]	S0	36	10	35	20	52
	S1	40	6	41	29	52
	S2	36	8	36	19	52
RH (extract air) [%]	S0	34	9	33	21	52
	S1	39	6	40	28	51
	S2	35	8	36	21	53

As mentioned previously, actual detection of occupancy was performed manually and the hours the classroom was fully occupied were fewer than assumed. With the baseline CO_2 setpoint of 500 ppm, the mean airflow rate during occupancy was generally closer to V_{max}, resulting in the lowest average CO_2 concentrations, air temperature, and RH, but higher O_3 and NO_2 concentrations. In contrast, for the S1 and S2 ventilation scenario, the lower supply airflow rates due to the higher CO_2 setpoint resulted in CO_2 peak concentrations above 1200 ppm. These short CO_2-peak episodes (5 – 30 minutes) took place during lunch breaks or teaching sessions when the class was fully occupied. However, the lower supply air flow rate also resulted in lower O_3 and NO_2 concentrations. A low ventilation rate and a high air temperature are generally not a good combination [17], although the CO_2 levels are well within the bounds where school performance would be negatively influenced [18].

3.3. *Effect of reducing V_{min}*

As seen in Figure 2, indoor concentrations of NO_2 during the nighttime with the ventilation on (S3) were comparable to when the ventilation was off. The elevated levels when the ventilation is off were most likely due to infiltration from outdoor air since there are no known emission sources of NO_2 indoors. An increase in NO_2 concentrations occurs first around 7 o'clock, which is during the traffic rush hours.

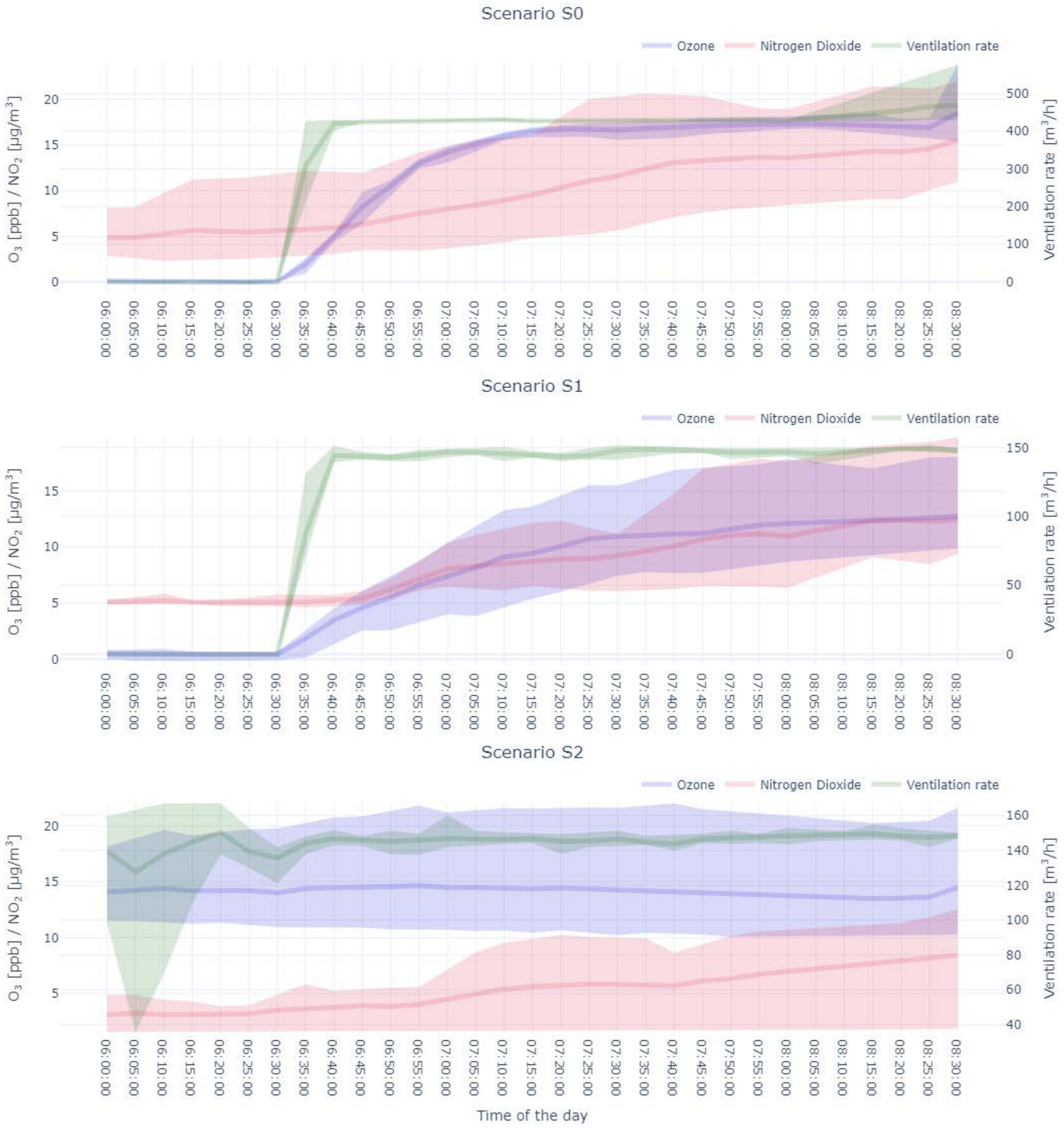

Figure 2. Average (min, max) concentration of O_3 and NO_2 for hours before occupancy for the three ventilation scenarios. Ventilation is usually turned on at 6:30 in the morning. Please note that the scales of the y-axis differ.

As seen in Figure 3, the S3 scenario resulted in the lowest indoor NO_2 concentrations. One of the major sources of NO_2 is road traffic, and NO_2 concentrations are generally higher during winter months compared to summer. Previously, NO_2 was measured for five weeks during winter months inside two classrooms at the same school, and mean concentrations between 15.4 – 45.9 µg/m^3 were reported, with peak concentrations of approximately 50 µg/m^3 [19]. Ventilation is usually turned off in the afternoon and switched on 2-3 hours before occupancy. With the ventilation off, O_3 concentrations have a relatively rapid decay and drop to approximately zero after three hours due to the removal by indoor surfaces or reactions with VOCs. Thus, as shown in Figure 2, when the ventilation is turned on, a prominent increase in O_3 concentrations can be seen for both the S0 and S1 scenarios. Moreover, lowering the V_{min} to 0.7 l/s/m^2 resulted in 35% lower O_3 concentrations on average. In contrast, if the ventilation is on during nighttime, the average indoor O_3 concentrations remained relatively constant at 14 ppb (~28 µg/m^3).

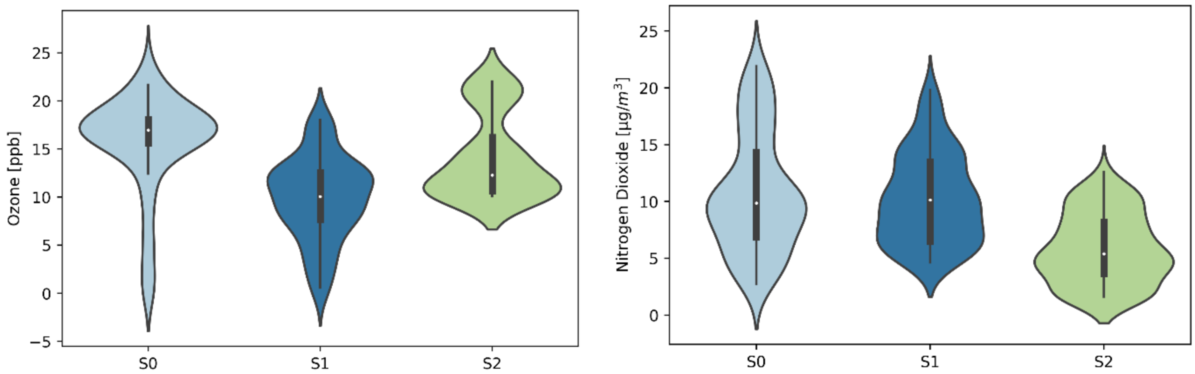

Figure 3. Violin plot of O_3 (left) and NO_2 (right) before occupancy (06:30 – 08:30) for the three ventilation scenarios. The white dot inside the box is the median.

Figure 3 shows that the S1 scenario results in the lowest median O_3 concentration before occupancy and S0 the highest. The reaction of ozone with certain VOCs, i.e., terpenes, to produce secondary organic aerosols (SOA) has been well studied. Typical SOAs that are initially produced are ultrafine particles, but would with time grow into larger particles, albeit still relatively small (<700 nm) [15,20,21]. Consequently, ozone would have a great impact on the indoor level of air pollutants. The level of V_{min} and the ventilation duration would thus influence the exposure before occupancy.

4. Conclusion and future outlook

In this study, different ventilation scenarios were evaluated in a classroom with demand-controlled ventilation for three weeks, focusing on exposure before occupancy. We found that reducing V_{min} to 0.7 l/s/m^2 would lower the ozone concentration by 35% compared to the baseline scenario with a V_{min} of 2.0 l/s/m^2. Moreover, continuous ventilation during night time with a low V_{min} resulted in almost as high O_3 concentrations as the baseline ventilation scenario. For NO_2, continuous ventilation during night time with a low V_{min} resulted in the lowest concentrations. As O_3 reacts easily with certain VOCs to produce secondary organic aerosols, the level of V_{min} and the ventilation duration would impact the indoor air quality upon entering the classroom. Further analysis of the VOC measurements and particle number concentrations would elucidate which ventilation strategy is most beneficial in terms of indoor air quality and energy use.

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