Ventilation strategies and indoor air quality in Swedish primary school classrooms

Downloaded from: https://research.chalmers.se, 2026-04-05 13:59 UTC

Citation for the original published paper (version of record):

Cabovska, B., Beko, G., Teli, D. et al (2022). Ventilation strategies and indoor air quality in Swedish primary school classrooms. Building and Environment, 226.
http://dx.doi.org/10.1016/j.buildenv.2022.109744

N.B. When citing this work, cite the original published paper.

research.chalmers.se offers the possibility of retrieving research publications produced at Chalmers University of Technology. It covers all kind of research output: articles, dissertations, conference papers, reports etc. since 2004. research.chalmers.se is administrated and maintained by Chalmers Library

(article starts on next page)

Building and Environment 226 (2022) 109744

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ventilation strategies and indoor air quality in Swedish primary school classrooms

Blanka Cabovská [a,*], Gabriel Bekö [b,c], Despoina Teli [a], Lars Ekberg [a,d], Jan-Olof Dalenbäck [a], Pawel Wargocki [b], Theofanis Psomas [a], Sarka Langer [a,e]

[a] Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Building Services Engineering, SE-412 96, Göteborg, Sweden
[b] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Lyngby, 2800, Denmark
[c] Department of Architecture, College of Architecture, Art and Design, Ajman University, Ajman P.O. Box 346, United Arab Emirates
[d] CIT Energy Management AB, SE- 412 88, Göteborg, Sweden
[e] IVL Swedish Environmental Research Institute, Environmental Chemistry, SE-400 14, Göteborg, Sweden

ARTICLE INFO

Keywords:
Indoor air pollutants
Thermal environment
Indoor environmental index

ABSTRACT

The present study aimed at investigating the effects of ventilation strategies on indoor air quality (IAQ) in schools. Measurements of thermal environment and IAQ were performed over 5 school days in 45 primary school classrooms in Gothenburg, Sweden, grouped into three categories according to their ventilation system: category A) natural or exhaust ventilation, or automated window opening; category B) balanced mechanical ventilation systems with constant air volume (CAV) and category C) balanced mechanical ventilation systems with variable air volume (VAV). The classrooms performed equally well with respect to temperature and relative humidity regardless of the ventilation system. The concentrations of the air pollutants in all classrooms were generally below the respective guideline values. The concentrations of CO_2, formaldehyde, $PM_{10,}$ and $PM_{2.5}$ were lower in the B and C category classrooms with higher ventilation rates than in the A category classrooms. Indoor Air Pollution Index integrating concentrations of multiple pollutants was significantly higher the A category classrooms, reflecting poorer IAQ. Majority of the classrooms had lower ventilation rates than the Swedish ventilation requirements. The periodically reduced ventilation rates in the classrooms with VAV systems did not lead to substantial increase in the measured indoor pollutant concentrations.

1. Introduction

Children spend substantial part of their day in school buildings. Moreover, they are a population group, which is especially sensitive to environmental pollution due to the immaturity of their immune system [1]. It is thus important to ensure that the environments where they spend substantial time do not pose risks to their health and well-being. The thermal environment is relevant for the children's well-being and learning [2–4]. Indoor air with concentrations of hazardous pollutants below permissible levels also contributes to health and satisfaction of school children as well as to their performance of schoolwork and learning [5–7]. Yet, many school buildings experience various problems with thermal environment and indoor air quality [8,9]. A report from the Public Health Agency of Sweden showed that 15% of the Swedish schools had 'poor' or 'rather poor' IAQ [10].

Good IAQ can be achieved by means of ventilation. The primary function of ventilation is to remove or dilute pollutants in the air emitted by building materials, building occupants themselves and activities performed indoors. International and national standards and legal requirements exist for ventilation rates in various indoor environments [11–13]. Concentration of CO_2 is typically used as an indicator for ventilation adequacy and IAQ in the absence of other indicators for IAQ [14]. Low ventilation rates and high CO_2 concentrations belong to the most often reported problems in school buildings, particularly in buildings ventilated naturally [5,15–17]. The use of mechanical ventilation usually results in higher ventilation rates and lower CO_2 concentrations [18–20]. However, correlations between CO_2 concentration and other pollutants such as benzene or formaldehyde are generally weak [21]. Therefore, low CO_2 concentration does not always indicate good IAQ; other indicators are needed.

---

* Corresponding author.
E-mail address: blanka.cabovska@chalmers.se (B. Cabovská).

https://doi.org/10.1016/j.buildenv.2022.109744
Received 21 June 2022; Received in revised form 19 October 2022; Accepted 22 October 2022
Available online 28 October 2022
0360-1323/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

An extensive review by Salthammer et al. [22] concluded that the challenges of ensuring high quality environments in school buildings partly lie in the absence of legally binding limit values for the majority of indoor air pollutants. Recommended guideline values exist for some of them such as particles (PM_{10}, $PM_{2.5}$), inorganic air pollutants nitrogen dioxide (NO_2), ozone [23], formaldehyde [24] and total volatile organic compounds (TVOC) [25]. In 2021, WHO published updated global air quality guidelines, recommended for both ambient and indoor air, among others for particulate matter (PM_{10} and $PM_{2.5}$), ozone and nitrogen dioxide [26].

Numerous studies measured various thermal parameters and air pollutants in schools. The studies with larger number of investigated schools focused on a single [27, 28, 29, 30] or a few parameters [7,15,19,21,31] while studies with smaller samples of schools tend to measure more parameters [32,33]. One study provides typical values for multiple indoor environmental parameters in schools across Europe [34]. Other studied parameters relevant in school buildings are often related to various building characteristics including the type of ventilation system (natural, mechanical-exhaust only, mechanical -balanced) [20], energy performance (low-energy schools) [18], location (urban, industrial, rural) [35], construction period, or to the occupants (children's age [15], exposure routes [30], and health and well-being [30,36,37]). Parameters characterizing IAQ and thermal environment in school buildings have been shown to be related to several parameters characterizing the buildings or their occupants [27,28,30,34].

In the present work, we investigate the impact of three ventilation strategies in primary school classrooms on thermal environment, indoor air quality and their perception by school children as assessed in a questionnaire survey. Results from the questionnaire survey and their associations with the measured indoor air quality indicators will be presented in a separate publication. The study contributes to existing knowledge by combining the assessment of measured and perceived indoor environmental parameters and the comparison of various ventilation strategies in a comprehensive way. The specific objectives of this article are 1) to evaluate the effect of ventilation strategies on thermal conditions and levels of individual indoor air pollutants, and 2) to calculate an aggregated indoor environmental index reflecting the measured conditions in the classrooms and explore its dependence on ventilation strategy.

2. Materials and methods

2.1. Schools

The school buildings were selected in cooperation with the property manager of primary schools in Gothenburg - Lokalförvaltningen (LF) located on the west coast in southern Sweden. The primary selection criteria for school buildings were the ventilation system used in the building and the year of construction.

The selected buildings were grouped into three categories named as category A, B or C, depending on the primary ventilation system and the type of system control used in the building (Table 1). The systems labelled as category A included natural ventilation, exhaust ventilation and automated window opening system. The common feature of these systems is that the outdoor air supplied indoors is untreated. The system labelled as category B was balanced mechanical ventilation with constant air volume (CAV) during daytime. The system labelled as category C included balanced mechanical ventilation with variable air volume (VAV). Neither the CAV nor the VAV systems have any recirculation of air. Instead, energy is recovered from the extract air to the supply air by means of a heat exchanger, typically a rotary heat exchanger (heat wheel) or a cross flow plate heat exchanger. This is the normal design of ventilation systems in Swedish schools and offices. Air recirculation is practically never used in such systems. Thus, the air supplied to the indoor environment is 100% conditioned and filtered outdoor air. Consequently, the room air was not filtered at all in any of the studied classrooms.

Typically, the ventilation systems in both category B and category C have been designed to meet the requirements set by the Swedish Work Environment Authority [38]. This requirement is based on the floor area and the number of occupants present (teachers and children), and it amounts to 7 L/s per person + 0.35 L/s per m^2. A typical classroom size is 60 m^2 with a ceiling height of 2.7 m. As an example, if such a classroom is intended to an occupancy of 20 people the ventilation rate requirement corresponds to an air change rate (ACR) of about 3.6 air changes per hour (h^{-1}). Many of the category A buildings are older than the legislative requirement described above. They were designed to rely on frequent breaks in combination with window airing.

In category C the ventilation rate is controlled with respect to the room temperature. The heating system is controlled by controlling the radiator supply temperature based on the outdoor temperature and by thermostatically controlled valves in the radiator system. The set-point for the heating system is typically 20 °C. Thus, no heat will be supplied through the radiators when the room temperature is higher than 20 °C. At room temperatures below 21 °C, the ventilation rate is at its minimum. The minimum value varies between schools, but typically it corresponds to about 0.35 L/s per m^2 floor area. When the room temperature increases above 21 °C, the ventilation rate increases. The ventilation rate is also controlled in order to limit the indoor carbon dioxide concentration. The set-point was typically chosen by school operators to be 1500 ppm, higher than suggested by most guidelines. For this reason, and due to normally lower CO_2 concentrations, the control with respect to CO_2 was rarely active in the classrooms.

The mechanical ventilation systems, both category B and C, are typically equipped with supply air filtration corresponding to a class around ISO ePM1 50% (class F7 according to the previous filter standard). According to REHVA Guidebook 11 [39] filters of this class can be expected to remove $PM_{2.5}$ particles with an efficiency of roughly 70%. The corresponding value for particles of the PM_{10} fraction is 90%. The applied maintenance strategy comprises annual replacement of the

Table 1
Categorization of the investigated classrooms according to ventilation system type.

Ventilation system category	Ventilation strategy	No. of school buildings	No. of classrooms	Age of the school building[a]	Classroom floor area[a]	Classroom volume[a]	Number of children[a]	Floor area per child[a]	Classroom volume per child[a]
				(years)	(m^2)	(m^3)		(m^2)	(m^3)
A	Natural ventilation, exhaust ventilation, automated window opening	7	14	107 ± 26	56 ± 10	191 ± 32	22 ± 3	2.7 ± 0.7	9.2 ± 2.1
B	Balanced supply-exhaust with constant air volume	8	15	61 ± 40	59 ± 6	175 ± 28	21 ± 3	2.8 ± 0.7	8.5 ± 2.2
C	Balanced supply-exhaust with variable air volume	8	16	38 ± 29	54 ± 6	157 ± 16	21 ± 4	2.7 ± 0.5	7.8 ± 1.6

[a] The entries in the table are average ± standard deviation.

filters. Thus, the filters in the different schools investigated in this study were likely at different stages of their service life, but none of them were older than one year. No additional air cleaning devices were installed in the classrooms.

In each school building two classrooms were selected where the measurements were performed except for one building where only one classroom was available. The final sample consisted of 45 classrooms in 23 school buildings with an even distribution of ventilation system categories. The majority of the classrooms were fifth grade (11–12 years age) to enable comparable results from a questionnaire survey conducted among the pupils.

The majority of the selected schools were located in urban areas, *i.e.* in the city center or in the residential areas of the city. Two schools were located in rural areas (outskirts of Gothenburg), but still in close proximity to main traffic roads. The age of the school buildings spanned over 127 years, with four buildings built in the year 1889, six between 1900 and 1950, seven in the period between 1951 and 1999 and six between 2000 and 2016. Modern mechanical ventilation system was installed after year 2000 in ten older school buildings (Table S1). The available data on building characteristics included the year of construction and year of upgrade of the ventilation system (where applicable), as well as the classrooms' floor area, volume, and air change rate (see section 2.2). All classrooms were occupied roughly between 8:00–14:30 every day with 21 children (median; range 15–30). The median floor area and volume of the classrooms were 58 m^2 (range 40–76 m^2) and 167 m^3 (range 129–260 m^3), respectively. The classrooms were mostly situated on ground floor or first floor. The classroom floor area-to-occupant ratio varied between 1.77 m^2/child and 3.99 m^2/child with a median of 2.73 m^2/child, which was similar to the mean per child floor area of 2.35 m^2/child reported for 64 Central European schools [33]. The median classroom volume-to-occupant ratio was 8.3 m^3/child (range 5.4–13.7 m^3) (Table S2).

2.2. Measurements

The measured parameters included indoor air temperature, relative humidity (RH), concentrations of carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), total volatile organic compounds (TVOC), C_1–C_{10} aldehydes (formaldehyde to decanal) and particulate matter (PM_{10} and $PM_{2.5}$). Hourly values of outdoor air temperature, RH, and concentrations of NO_2, ozone, PM_{10} and $PM_{2.5}$ were collected from the municipal ambient air monitoring station of the City of Gothenburg. For the outdoor monitoring, temperature and RH were measured using Rotronic HC2A-S3 sensor; NO_2 was measured using Teledyne T200 NO/NO_2/NOx analyzer with chemiluminescence detection; ozone was measured using Teledyne T400 UV absorption analyzer; PM_{10} and $PM_{2.5}$ were measured using TEOM Tapered element oscillating microbalance (Thermo Fisher Scientific TEOM 1405DF). The data are available in an open database [40]. Outdoor CO_2 concentrations were not available at the monitoring station. We have assumed a value of 400 ppm (2021 global average [41]).

Measurements were performed during the 2019/2020 heating season just before the pandemic broke out. The duration of monitoring in each classroom was 5 school days (1 school week). The measurements were launched on Monday morning after installation of the measurement equipment before the children entered the classroom and ceased on Friday afternoon after the children left the classroom. Monitoring equipment was moved each week between schools and placed on shelves or cabinets out of the children's reach and away from direct internal heat sources and direct solar radiation. The samplers of the air pollutants were placed 1.5–2 m above the floor and about 50 cm from the ceiling.

Air temperature, RH and concentrations of CO_2 were monitored using a Wöhler CDL210 (Wöhler Technik GmbH, Germany; calibrated according to the users' manual) with a 2-min time resolution. The accuracy reported by the manufacturer is ±0.6 °C, ± 3% and ±50 ppm (or ± 5% whichever is greater) for temperature, RH and CO_2 concentration, respectively. Particles (PM_{10} and $PM_{2.5}$) were measured using an optical particle counter (TSI DustTrak DRX, model 8533, factory calibrated). The instrument was operated with a time resolution of 10 min and has an accuracy of ±0.1% of reading or 0.001 mg/m^3, whichever is greater. The air change rate (ACR) was calculated from the exponential, first order decay curves of occupant-generated CO_2 concentration vs. time, in line with the standard procedure for determination of air change rate by means of a tracer gas decay method [42] once the children left the classrooms for breaks or at the end of the school day. The length of each analyzed concentration decay typically corresponded to at least the time for one air change (the nominal time constant of the ventilation). All investigated rooms were dedicated to school activities comprising teaching in full or half class. When class was over, the rooms were left empty. Consequently, the risk that the concentration decay was biased by any CO_2-generation during the decay is minimal. Moreover, the standard procedure in these schools is to keep the classroom doors closed and locked between classes. Thus, the concentration decay was not influenced by any substantial internal transfer of air through door openings. The reported air change rate values are an average of five measurements in each classroom, typically measured on different days. In category A classrooms, windows were operated by the teachers, in the same way during the monitoring weeks as during other weeks; windows were opened when the teacher determined that the air quality called for that. The window openings influenced the ventilation rate substantially. The individual ACR-values used for calculation of the reported average value spread over a wider range for category A (average relative standard deviation 46%) classrooms than for category B (12%) and C (13%) classrooms. The ventilation rate in each classroom (L/s) was determined from the air change rate and the room volume.

Passive/diffusive samplers were applied to measure NO_2 and ozone [43]. Their concentrations were analyzed by wet chemical techniques using a spectrophotometric method (NO_2) and ion chromatography (O_3). The analytical procedures are accredited by the Swedish accreditation agency SWEDAC. The measurement uncertainty was 10% at 95% confidence level. The limit of detection (LOD) was 1 μg/m^3 for NO_2 and 9 μg/m^3 for ozone.

C_1–C_{10} straight chain aldehydes (from formaldehyde to decanal) were sampled using DSD-DNPH Aldehyde Diffusive Sampling Devices (Supelco, Bellefonte, PA). The sampling period and the subsequent analytical technique (solvent extraction and high-performance liquid chromatography) followed the ISO 16000-4 standard [44]. The LOD was 0.1 μg/m^3 for formaldehyde and between 0.5 and 2 μg/m^3 for the other aldehydes.

Volatile organic compounds (VOCs) were passively sampled on Tenax TA (PerkinElmer) adsorbent tubes and analyzed in compliance with ISO 16017-2 [45]. The Tenax tubes were thermally desorbed (Markes International, Unity 1 and Ultra, 5 min, 250 °C) and analyzed by gas chromatography/mass spectrometry (GC/MS). The gas chromatograph (GC) was an Agilent 6890 equipped with a mass selective (MS) detector (Agilent 5973 N) in electron impact mode for compound identification. The GC was equipped with a CP Wax 52C (Agilent) capillary column (Polyethylene glycol phase, 60 m, 0.32 mm i.d., 1.2 mm film thickness) and used helium as carrier gas. The GC oven temperature program was started at 50 °C and increased to 100 °C at 4 °C C/min., then increased to 220 °C at 8 °C/min, which was maintained for 10 min. The VOCs were primarily evaluated as total VOC (TVOC), a sum of all individual compounds eluting between n-hexane and hexadecane (C_6 to C_{16}) and quantified as toluene equivalent concentrations using the uptake rate and the response factor of toluene. Additionally, eleven individual VOCs were quantified specifically: benzene, toluene, m-xylene, α-pinene, limonene and 2-ethylhexanol using their compound specific uptake rates and response factors, and n-hexane, ethylbenzene, o- and p-xylene and styrene in toluene equivalents. The LOD for the TVOC was 10 μg/m^3 based on 3 times the signal-to-noise ratio, and between 0.1 μg/m^3 and 1 μg/m^3 for the individual VOCs.

The results obtained from the passive sampling (NO_2, ozone, formaldehyde, TVOC) are the concentrations integrated over the whole sampling week (called "weekly average" throughout the article). Temperature, RH, CO_2 and particles from the time-resolved measurements were aggregated into weekly averages and weekly averages for occupied hours (8:00–14:30 during the school days; called "occupied time average" throughout the article). The values < LOD were replaced by ½ LOD; this was the case for ozone, benzene, toluene, α-pinene, limonene, 2-ethylhexanol, propanal, pentanal, hexanal and heptanal.

2.3. Indoor environmental index

The Indoor Environmental Index (IEI) proposed by Moschandreas and Sofuoglu (2004) [46] was calculated to characterize the conditions in the classrooms by aggregating the individual concentrations of indoor air pollutants (the weekly averages) into one parameter. Detailed description of the index can be found in the Supporting Information (text, Fig. S1, Table S3). IEI (Equation 1in SI) is an arithmetic mean of the Indoor Discomfort Index (IDI) and the Indoor Air Pollution Index (IAPI). IDI relates observed values of temperature and relative humidity to their optimal values and to upper and lower comfort limit levels (Equation 2in SI). IAPI is created by locating the observed concentrations of air pollutants within the range of the observed values (maximum and minimum) and relating them to their respective demarcation values, which are the recommended IAQ guideline values (Equation 3in SI). The index is a unitless number between 0 (excellent IEQ) and 10 (worst IEQ). To consistently use only results from the same sampling period, weekly averages were used both for the gaseous air pollutants and the particles. The input values can be found in Tables S4 and S6 – S8. WHO 2005 [23] and WHO 2021 [26] guidelines were used as the demarcation values for NO_2, ozone, PM_{10} and $PM_{2.5}$.

2.4. Statistical analyses

Kruskal-Wallis test was used to examine the differences in the measured parameters across the three different ventilation categories. Pairwise differences were tested for significance using Mann-Whitney *U* test. Spearman rank correlations were calculated to determine the correlations between the measured parameters, using the weekly averages, the indices and the building characteristics. Statistical significance was defined as $p \leq 0.05$ (2-Tail). Statistical calculations were performed with SPSS software.

3. Results

Results summarizing the measurements in all classrooms are presented in Table 2. Valid data were collected in all classrooms for all parameters except for the concentration of ozone (29 classrooms, 64%, with concentration > LOD). Further results are shown in the Supporting Information (Tables S4–S9). Results of the Kruskal-Wallis tests of differences in all variables by ventilation categories are shown in Table S10.

3.1. Temperature, RH, CO_2, ACR

Weekly averages and occupied time averages of air temperature, relative humidity and CO_2 concentration are presented in Table S4 and the Kruskal-Wallis statistics in Table S10. The median values of temperature and relative humidity (Table 2) were within the range defined by the EN 16798–1:2019 [12] standard (20–24 °C and 25–60% RH) and by the Swedish regulations (20–24 °C) [38,47]. The differences between the weekly averages and the occupied time averages of temperature (Mann-Whitney, $p = 0.11$) and relative humidity (Mann-Whitney, $p = 0.56$) across all classrooms were not significant. The differences in temperature and relative humidity between the ventilation categories (both weekly averages and occupied time averages) were not statistically significant either.

The median temperatures were lower and had a narrower range than those observed in the 64 Central European schools (median 22.8 °C, range 18.7–25.9 °C) [33], in the 70 schools in Southwestern US (average 23 °C) [7], in 40 schools in Midwestern US (average 22.4 °C) [48], in 115 schools across 23 European countries (median 22 °C, IQR = 3.0 °C) [34] and in classrooms in Portugal (median 21.9 °C, IQR = 3.6 °C) [32].

The median values of RH in our study were similar to those reported in Central European schools (median 35%, range 20–55%) [33], in other European schools (median 40%, IQR = 14%) [34], in Southwestern US schools (40%) [7] and in Midwestern US schools (average 40%) [48] but lower than in Portuguese classrooms (median 58%, IQR = 18.2%) [32].

The median CO2 concentration across all classrooms (Table 2) was well below the recommended guideline value of 1000 ppm. [49] It was below the medians observed in European schools (1284 ppm and 1370 ppm) [33, 34], in French elementary schools (1123–1329 ppm) [20], in Southwestern US schools (average 1780 ppm) [7] and in Midwestern US schools (average 1171 ppm) [48]. The classrooms in this study were well ventilated, with median air change rate of 3.2 h-1, which is much higher than in the French (0.11–0.12 h-1) [20], European (0.40 h-1) [34] and Central European (1.49 h-1) [33] schools.

Table 2
Summary of the measurements in all classrooms.

Parameter	Median	Interquartile range	Min	Max	Recommended guideline values	Reference
Temperature, °C, all week	20.8	1.4	18.7	23.4	20–24	EN 16798–1:2019 12], AFS 2020:1 [38], FoHMFS 2014:17 [47]
Temperature, °C, occupied time	21.2	1.2	19.4	24.0	20–24	EN 16798–1:2019 [12], AFS 2020:1 [38], FoHMFS 2014:17 [47]
RH, %, all week	34	9	22	54	25–60	EN 16798–1:2019 [12]
RH, %, occupied time	35	9	20	57	25–60	EN 16798–1:2019 [12]
CO_2, ppm, all week	520	170	450	960	1000	FoHMFS 2014:18 [49]
CO_2, ppm, occupied time	690	190	540	1630	1000	FoHMFS 2014:18 [49]
Air change rate (ACR), h^{-1}	3.2	1.7	0.31	5.1	[a]	AFS 2020:1 [38], FoHMFS 2014:18 [49]
NO_2, µg/m^3	9.7	0.48	2.9	32	40/10	WHO, 2005/2021 (annual mean) [23,26]
Ozone, µg/m^3	10	0.25	4.5[b]	56	100	WHO, 2005/2021 (8-h average) [23,26]
TVOC, µg/m^3	120	72	35	590	300	Fromme et al., 2019 [25]
Formaldehyde, µg/m^3	9.4	6.5	1.7	27	100	WHO, 2010 [24]
PM_{10}, µg/m^3, all week	10	7	2	28	20/15	WHO, 2005/2021 (annual mean) [23,26]
PM_{10}, µg/m^3, occupied time	21	11	8	51	50/45	WHO, 2005/2021 (24-h mean) [23,26]
$PM_{2.5}$, µg/m^3, all week	7	5	1	18	10/5	WHO, 2005/2021 (annual mean) [23,26]
$PM_{2.5}$, µg/m^3, occupied time	13	8	5	29	25/15	WHO, 2005/2021 (24-h mean) [23,26]

[a] Standards specify ventilation rates per floor area and number of occupants. Air change rate is a result of ventilation rate and size of a room.
[b] ½ LOD.

The CO2 concentrations measured in individual classrooms (averages during occupied time) are presented according to the ventilation categories in Fig. 1. The median CO2 concentration of 1100 ppm in the classrooms with A category ventilation was much higher than in the classrooms with the ventilation systems B and C (median CO2 440 ppm and 480 ppm lower, respectively). Large variations in CO2 concentrations were observed in the classrooms with the category A system; 64% of these classrooms had an occupied time average above 1000 ppm recommended by the Public Health Agency of Sweden [49]. In the classrooms with systems categorized as B and C the variation was very low, and the maximum measured levels were generally below 800 ppm. There were statistically significant differences in CO2 concentrations between the classrooms with ventilation systems A and either B or C, but there was no difference between classrooms with systems B and C. The corresponding plot for the weekly average CO2 concentrations can be found in the Supporting Information (Figure S2).

The ACR-values in the classrooms with different ventilation categories are shown in Fig. 2a; the raw data are presented in Table S5 and the median values in Table 2. The classrooms with ventilation category A had significantly lower ACR-values than those with the systems categorized as B and C; no significant difference was observed between systems categorized as B and C. On the contrary, the median ACR-values in classrooms without any ventilation system and classrooms with some ventilation system (exhaust or balanced ventilation used for limited time) in France did not differ significantly.20 These results may reflect the differences in construction practices of school buildings in the two countries, the type and operation pattern of the ventilation systems and occupant behavior such as window opening.

The ratio of the actual ventilation rates (expressed as L/s) in the classrooms (calculated from the ACR-values and the classrooms' volumes) to the ventilation rates required by the Swedish Work Environment Authority [38] based on the floor area and the number of children (7 L/s per person + 0.35 L/s per m^2) is shown in Fig. 2b (data in Table S5). These ratios indicate that the ventilation rates were below the Swedish requirements [38,49] in all the A category classrooms and in 50% of both B and C category. The ratios for the category A classrooms were significantly different from both B and C category classrooms. There was no significant difference between B and C category classrooms (Table S10).

The median ventilation rate per person shown in Fig. 2c is 3.0 L/s per person for category A, while it is 6.6 L/s per person and 7.7 L/s per person for categories B and C, respectively (Table S10). Ways to ensure the required ventilation rates in category A classrooms are limited and verification of the ventilation rates in these classrooms is difficult. Category B and C classrooms with insufficient ventilation may have had an increased number of children compared to the nominal system capacity and their systems were not properly adjusted to address the new loads.

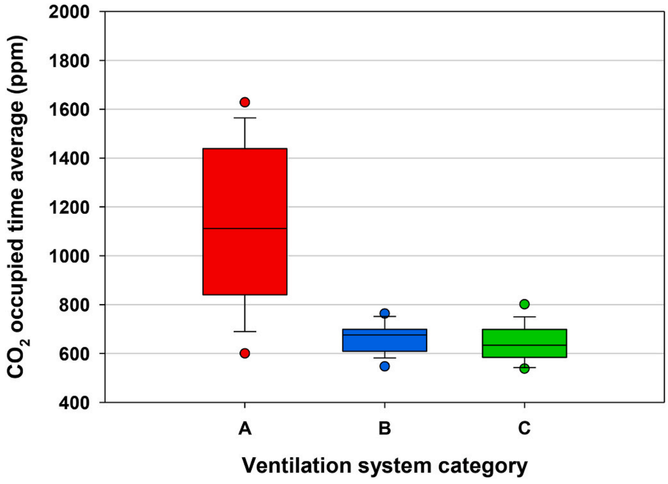

Fig. 1. CO2 concentration during occupied time in the classrooms with the three ventilation categories.

Based on the tabulated values of CO2 generation rates according to age and level of physical activity [50] we assume that the school children and teachers together generate carbon dioxide at an average rate of about 12–13 L/h per person. Together with the median ventilation rates shown in Fig. 2c, the steady state indoor concentration of CO2 is estimated to be about 1500 ppm in category A classrooms and about 900 ppm in category B and C classrooms. These values can be expected to prevail towards the end of lectures when the concentration approaches steady state. The values are substantially higher than the values shown in Fig. 1, which represent the concentration expressed as an average during the whole working day including breaks. The calculated steady-state CO2 concentrations can be compared to concentrations measured in the classrooms. It may be justified to assume that the 95-percentile of the measured CO2 concentrations (occupied time averages) can be used as an estimate of the steady-state concentrations occurring by the end of each lecture. The medians of these percentiles were 1840 ppm for category A, 920 ppm for category B and 850 ppm for category C. These values correspond fairly well with the calculated steady-state CO2 concentrations. The steady state concentrations can be even higher assuming higher CO2 generation rates, as suggested in some literature [51, 52].

3.2. Air pollutants

Indoor concentrations of NO_2, ozone, TVOCs, formaldehyde, PM_{10} and $PM_{2.5}$ as well as outdoor concentrations of NO_2, ozone, PM_{10} and $PM_{2.5}$ and the corresponding indoor-to outdoor (I/O) concentration ratios are summarized in Table 2 and Table S6-S10. In the following subsections, the results from this study are presented and compared with recommended levels as well as with results from the literature. The results are then discussed in relation to the ventilation categories.

3.2.1. Inorganic air pollutants NO_2 and ozone

The median NO_2 concentration of 9.7 μg/m^3 across all classrooms (Table 2) was below the World Health Organization's (WHO) recently recommended annual mean NO_2 concentration of 10 μg/m^3 [26]. It was also below the median NO_2 concentration of 21.1 μg/m^3 (range 6.0–68.5 μg/m^3) reported in the review that included 47 scientific publications examining indoor NO_2 samples from >960 classrooms in 354 school buildings around the globe [27]. The weekly averages were all below the 2005 guideline value of 40 μg/m^3 [23] but exceeded the 2021 guideline value in 47% of the classrooms.

The median ozone concentration of 10 μg/m^3 across all classrooms (Table 2) was well below the WHO guideline value of 100 μg/m^3 for maximum 8-h mean ozone concentration [23,26]. It was comparable with the median ozone concentration of 8.5 μg/m^3 (range 0.8–114 μg/m^3) reported in the review that included 13 studies examining 525 indoor ozone samples in 91 school buildings in European countries, Mexico and China (Shanghai) [28]. Ambient ozone concentrations peak during late spring/early summer. For this reason, the reported median ozone concentration would likely be higher if the measurements in the classrooms were performed outside the heating season.

Traffic-related and industrial emissions are the major outdoor sources of NO_2, and higher concentrations are observed during winter. Ozone is produced photochemically through a complex set of gas phase reactions involving organic compounds, nitrogen oxides, carbon monoxide and sunlight, thus the elevated outdoor levels are frequently observed in polluted areas with much sunshine during spring and early summer. With negligible indoor sources, outdoor to indoor transport is the major source of indoor NO_2 and ozone. The rather low indoor concentrations of NO_2 and ozone in this study were likely caused by the low outdoor levels (Table S6).

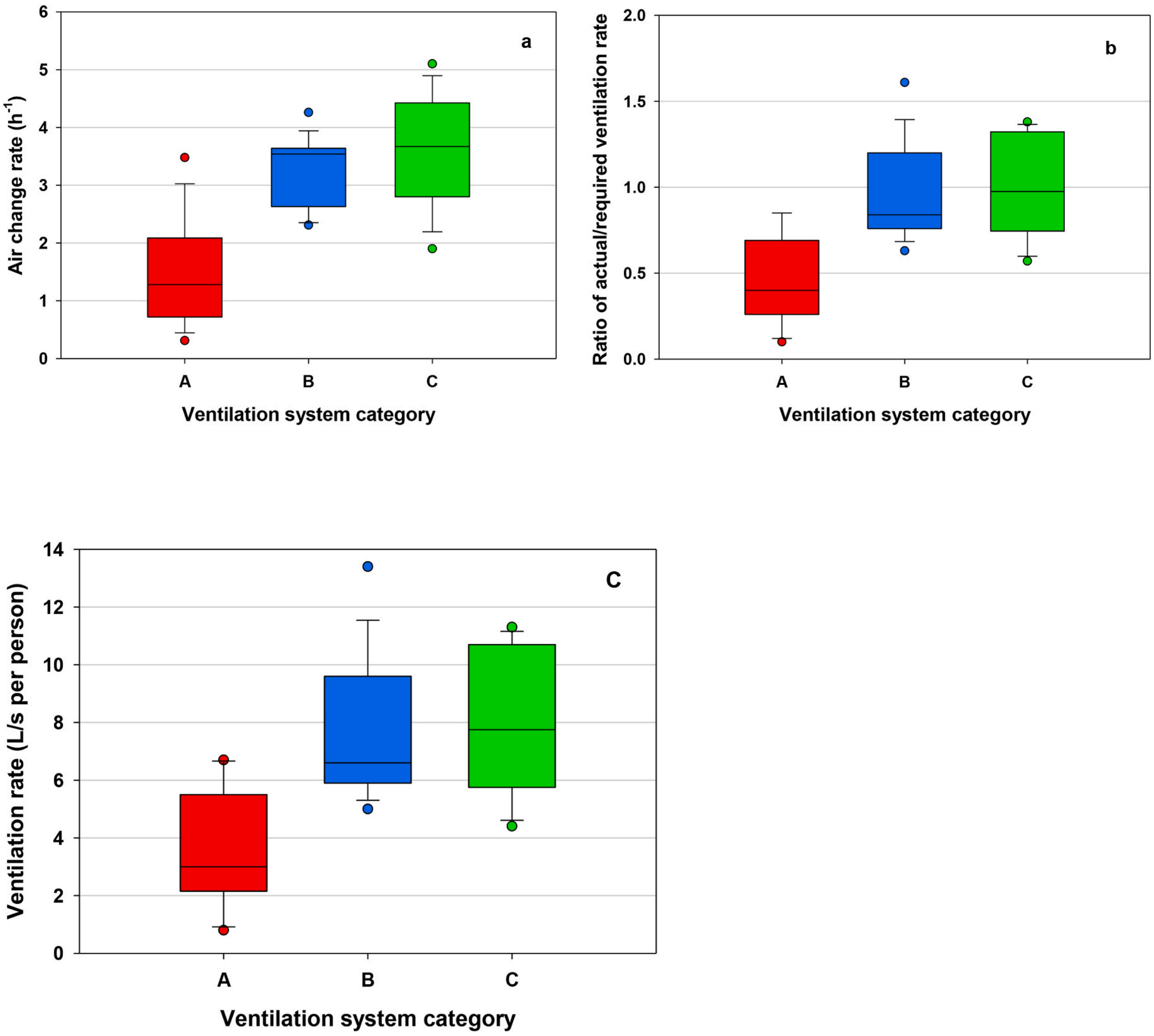

Fig. 2. a) Measured air change rate; b) ratio of actual-to-required ventilation rates in the classrooms with the three ventilation categories; c) actual ventilation rates per person.

3.2.2. *Indoor-to-outdoor concentration ratios of NO_2 and ozone*

The I/O concentration ratio of NO_2 (Table S6) depends on outdoor (traffic) and indoor combustion sources, season, ventilation rate and surface removal [27,53]. The reported mean (± standard deviation) I/O concentration ratio of NO_2 was 0.83 ± 0.55 and 0.87 ± 0.19 in naturally and mechanically ventilated schools around the world, respectively [53] and 0.80 ± 0.55 in European schools [54]. The I/O concentration ratios of NO_2 in this study (Fig. S5, median 0.59, range 0.19–1.96) were mostly within the range reported in other studies. The I/O concentration ratios for ozone reported in the literature were most often in the range 0.02–0.9, with lower values in buildings with low ventilations rates [55, 56]. The I/O concentration ratios for ozone in this study (Table S6 and Fig. S6, median 0.20, range 0.10–1.00) were within the range of I/O concentration ratios for school buildings in the literature [28,54].

The type of ventilation system was associated with indoor NO_2 and ozone concentrations and with the I/O concentration ratios. Box plots of concentrations and I/O concentration ratios for NO_2 and ozone by the ventilation categories can be found in Figs. S3–S6. Median concentration and I/O concentration ratio of NO_2 was highest for category B. The difference was statistically significant compared to the classrooms with ventilation systems A and C. Median concentration and I/O concentration ratio of ozone was the highest in the classrooms with ventilation category C. The difference in concentrations was statistically significant between the classrooms with ventilation category A and C. The differences in I/O concentration ratios were significant between all three categories. There were no differences in outdoor levels of ozone (Kruskal-Wallis, $p = 0.74$) and NO_2 (Kruskal-Wallis, $p = 0.95$) between the school buildings with different ventilation categories so the differences in indoor concentrations and I/O concentration ratios can be attributed primarily to ventilation and to transformations occurring either in the gas-phase or on surfaces. The indoor NO_2 concentrations and the resulting I/O concentration ratios were higher in two classrooms of one school compared with the rest of the schools (I/O concentration ratio close to 2) and one classroom of another school had an average ozone concentration identical to that outdoors. These cases reflect potential indoor sources or measurement errors.

3.2.3. *TVOC and formaldehyde*

The TVOC concentrations did not differ significantly between the classrooms with the three ventilation strategies (Fig. S7). The TVOC concentrations in all schools except one (median 120 μg/m^3, Table 2) were below the recommended long-term guideline value [25] of 300 μg/m^3 (Table S7). The TVOC levels from this study cannot be directly compared with results from other studies, as most other studies quantified sets of preselected individual VOCs [17,33,34]. The studies also differ in measurement methods, in the number of included VOCs and in the specific VOCs included. Our median TVOC level is similar to the median TVOC of 179 μg/m^3 reported for 63 German day-care centres

[57].

The median formaldehyde concentration of 9.4 μg/m^3 (Table 2) was well below the WHO guideline of 100 μg/m^3 for a 30-min mean concentration [24]. It is close to the long-term (one year) indoor guideline value of 10 μg/m^3 for formaldehyde suggested by the Public Health England [58]. The long-term guideline value of 10 μg/m^3 was exceeded in 47% of the investigated classrooms (Table S7). The median formaldehyde concentration was half of the median value measured in 310 French nurseries, kindergartens and elementary schools (19.7 μg/m^3) [16] and it was similar to the levels reported for 64 Central European schools (7.95 μg/m^3) [33] and 115 European schools (11.3 μg/m^3) [34]. Formaldehyde levels were statistically significantly higher in classrooms with ventilation category A than in classrooms with ventilation categories B and C; no differences were seen between classrooms with systems B and C (Fig. 3).

3.2.4. Particulate matter PM_{10} and $PM_{2.5}$

The medians of the weekly average PM_{10} and $PM_{2.5}$ concentrations were 10 μg/m^3 and 7 μg/m^3, respectively (Table 2). These levels are below the annual mean PM_{10} and $PM_{2.5}$ concentrations of 20 μg/m^3 and 10 μg/m^3, respectively, recommended by WHO (2005) [23] (Table S8). However, the median $PM_{2.5}$ is above the annual mean $PM_{2.5}$ concentrations of 5 μg/m^3 recommended by WHO (2021) [26]. The weekly averages exceeded the guideline values in 18% (2005) and 22% (2021) of all cases for PM_{10} and in 24% (2005) and 73% (2021) of all cases for $PM_{2.5}$, predominantly in the classrooms with ventilation category A.

The medians of the average PM_{10} and $PM_{2.5}$ concentrations during occupied time (Table S9) were 21 μg/m^3 and 13 μg/m^3, respectively. These levels exceed the recommended WHO annual mean levels but were below WHO's recommended 24-h mean PM_{10} and $PM_{2.5}$ [23,26]. The short-term guidelines were exceeded in 2% (2005) and 9% (2021) of all cases for PM_{10} and 9% (2005) and 31% (2021) of all cases for $PM_{2.5}$, and this was the case only in classrooms with ventilation category A.

The median of the weekly average PM_{10} concentration (10 μg/m^3) was well below the median of 102 μg/m^3 reported in a review of indoor PM_{10} in schools around the world. The median weekly $PM_{2.5}$ concentration (7 μg/m^3) was also significantly lower than the median of 23 μg/m^3 reported for schools around the globe [29]. The median PM_{10} concentration during occupied time (21 μg/m^3) was much below the weighted PM_{10} mean of 182 μg/m^3, and the median $PM_{2.5}$ concentration during occupied time (13 μg/m^3) was also below the weighted $PM_{2.5}$ mean of 50 μg/m^3 reported in a review of 50 school studies during occupancy [30].

The ventilation strategies had a considerable effect on the indoor PM levels. Both PM_{10} and $PM_{2.5}$ concentrations during occupied time were significantly higher in the classrooms with ventilation category A compared with ventilation categories B and C. There were no significant differences between classrooms with ventilation categories B and C (Fig. 4). The same trend was observed for the PM_{10} and $PM_{2.5}$ weekly average concentrations (Figs. S8–S9). The higher PM levels in the category A classrooms may be explained by the lower ventilation rates and thus less removal by ventilation of PM generated indoors and the lack of particle filtration in the air penetrating from outdoors. The median PM concentrations during the occupied time were approximately twice as high as the medians of the weekly averages for categories B and C; it was about 50% higher for category A. It indicates the importance and magnitude of indoor PM sources such as resuspension and particles brought in and generated inside by the occupants (e.g., on shoes, clothes, skin).

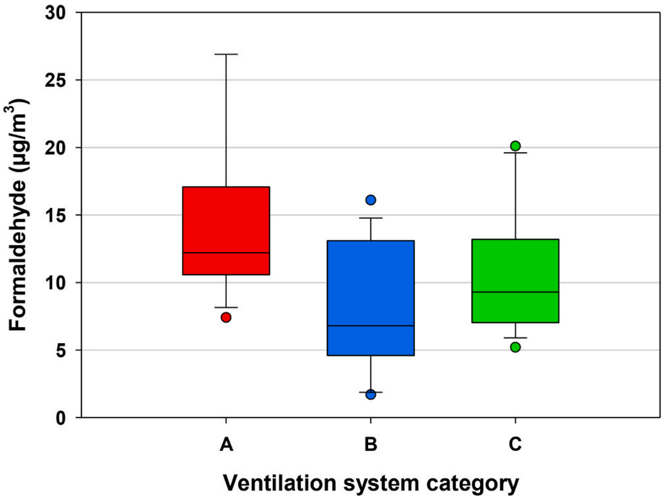

Fig. 3. Weekly average formaldehyde concentrations in the classrooms with the different ventilation categories.

Typical time series of $PM_{2.5}$ concentrations during the school week in classrooms with ventilation category A and C are shown in Figs. S10 and S11, respectively. These time series were similar across all classrooms of a given category. The time series of PM_{10} followed a similar trend, albeit at higher concentrations. In all cases, the concentrations of PM increased sharply in the mornings when the children entered the classroom and decreased in the afternoon when the children left the classroom. During the school days, the concentrations increased when the children were present in the classrooms and decreased during breaks and lunch. During the unoccupied hours, the concentrations were close to zero. As exemplified in Figs. S10 and S11, the time course of the PM concentrations directly correlated with the time course of the occupant-generated CO_2 concentrations. These findings support the hypothesis that PM was mostly generated indoors and was associated with the presence of occupants.

The difference in PM concentrations between categories B and C were small, but a larger variability was observed in category C, highlighting the importance of effective operation and control of these more advanced systems.

3.2.5. Indoor-to-outdoor concentration ratios of PM_{10} and $PM_{2.5}$

The median I/O concentration ratio for weekly PM_{10} across all classrooms was 0.91, for occupied time it was 1.62. The corresponding I/O concentration ratios for $PM_{2.5}$ were 1.37 and 2.21. The I/O concentration ratios for PM_{10} during occupied hours in schools reported in the literature are ~1, slightly below our results. The reported I/O concentration ratios for $PM_{2.5}$ are ~1.5 [30]. Indoor sources seem to contribute more to indoor PM levels in our study than in earlier ones. The I/O concentration ratios of the particle concentrations differed with the ventilation strategy (Figs. S12–S15). They were consistently and significantly higher in the classrooms with ventilation category A than in the classrooms with the two other ventilation categories; no difference was seen between classrooms with B and C category ventilation. Higher ventilation rates (removing indoor generated PM) and the presence of particle filtration in the ventilation system (removing PM from the incoming outdoor air) may explain the lower PM levels and I/O concentration ratios in the classrooms with ventilation categories B and C than in category A classrooms. Moreover, in the classrooms without mechanical ventilation with air filtration, higher ACR may lead to more transport of PM from the outdoors.

It should be noted that the concentrations of corresponding indoor and outdoor air pollutants were not measured using identical measurement techniques. Additionally, the outdoor values were obtained from one fixed monitoring station. It does not reflect the local variations given the different geographical location of the schools. These two facts may to some extent confound the results of our indoor to outdoor analysis.

3.3. Indoor environmental index (IEI)

No statistically significant differences in the Indoor Discomfort Index

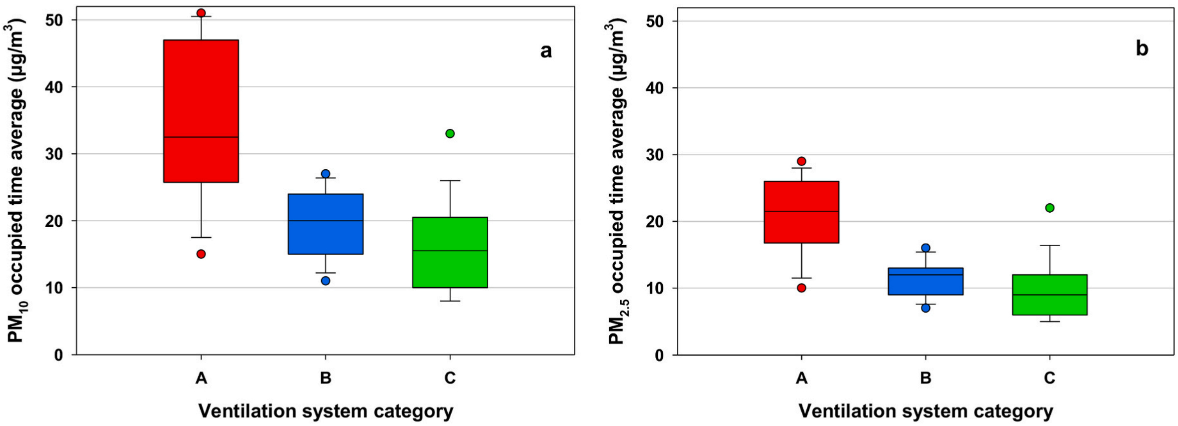

Fig. 4. Occupied time average a) PM10 and b) PM2.5 concentrations in the classrooms with different ventilation categories.

(IDI) were found between the classrooms with different ventilation categories (Fig. 5, Table S10). The quality of the thermal environment was thus similar in the classrooms with the three types of ventilation systems. The Indoor Air Pollution Index (IAPI) was significantly higher in classrooms with category A ventilation, reflecting poorer indoor air quality. The Indoor Environmental Index (IEI), which is the arithmetic mean of the other two indices, was highest in the category A classrooms, lowest in the category C classrooms (Fig. S16). The difference between the two was significant (Table S10).

Each index is a unitless number between 0 (excellent) and 10 (worst). The absolute values of the indices mirror the range of the measured values and the distance of the measured values from the corresponding reference values for each included variable. IDI becomes zero when the measured average values of temperature and RH (Table S4) equal the optimum values defined in corresponding standards or guidelines. The worst case for the IAPI (IAPI = 10) occurs when the measured average concentrations of all included individual variables (Tables S6–S8) equal their respective reference (demarcation) values (Table S3). In this study, NO_2, PM_{10} and $PM_{2.5}$ above the reference values are the main contributors to the elevated IAPI.

The choice of the guideline values is critical for the absolute value of the IAPI. Figures S17 and S18 show the IAPI and IEI calculated using WHO's 2021 guideline values. The values of the indices increased as the 2021 guideline values for NO2, PM_{10} and $PM_{2.5}$ are lower than the 2005 values. It did not, however, change the trend of the results. It should be noted that the indices are used here as comparative tools to assess the indoor environment across the classrooms with different ventilation systems within this study. A harmonized selection of the type of the air pollutants considered, the comfort limits (IDI) and the demarcation values (IAPI) is needed to make the indices comparable between studies. Moreover, the results of the chemical measurements, and thus the indices, reflect weekly average levels. Time-resolved measurements of the gaseous air pollutants are recommended in order to assess the children's exposure during school time and the true effect of the ventilation strategies on exposure.

3.4. *Correlation between measured variables and building characteristics*

Spearman rank correlation tests were performed on the measured variables and selected building characteristics. Two datasets were used. Weekly average concentrations of the gaseous air pollutants were used in both datasets. For temperature, RH, CO_2, PM_{10} and $PM_{2.5}$, weekly averages were used in one dataset and occupied time averages in the other dataset. The differences between weekly data and occupied time data were small. The Spearman rank correlation coefficients for the selected variables are presented in Table S12. Some of the stronger and significant ($p < 0.05$) correlations were as follows: ACR was the main driver of the concentrations of ozone, CO_2, formaldehyde, PM_{10} and $PM_{2.5}$. Similar relationships were observed in 40 schools in Midwestern US, where ventilation rate was strongly associated with concentrations of formaldehyde and particulate matter [48]. The IEI was mainly driven by concentrations of TVOC, PM_{10} and $PM_{2.5}$. Additionally, the year of construction was strongly related to ACR and room volume and thus to the concentrations of ozone, CO_2, PM_{10} and $PM_{2.5}$.

4. Discussion

Installation of balanced mechanical ventilation systems is especially

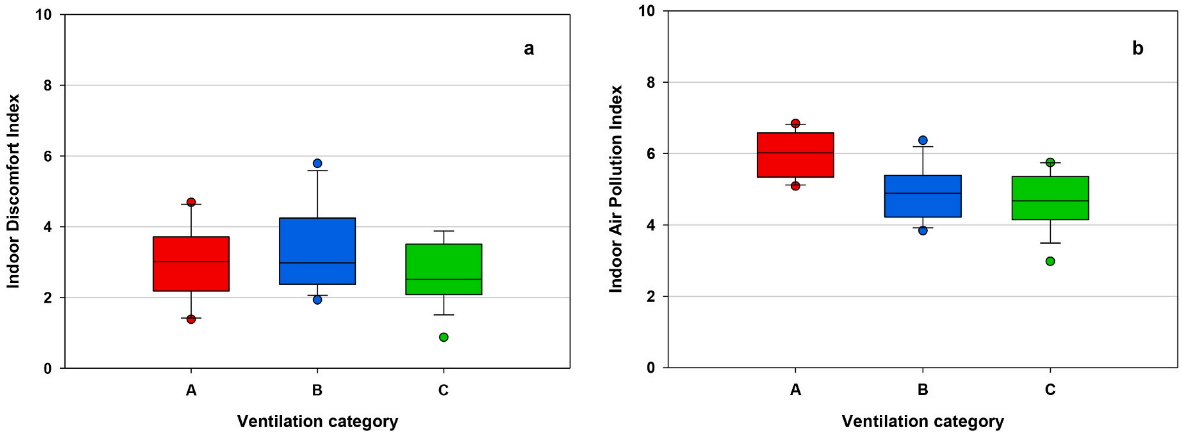

Fig. 5. Box plots of the a) IDI and b) IAPI in the classrooms with different ventilation categories. IAPI is based on the WHO's 2005 guideline values.

beneficial for the reduction of PM concentrations in the classrooms, which is an advantage in light of the recently lowered recommended PM_{10} and $PM_{2.5}$ guideline values. The mechanisms providing lower PM concentrations in these classrooms are 1) reduced supply of particles from outdoors due to supply air filtration (in Sweden, typically corresponding to filter class MERV-13) and 2) maintained ventilation rate during occupancy, removing PM generated by people and their activities indoors.

Classrooms with natural ventilation or mechanical exhaust only ventilation will have higher PM concentrations due to the absence of supply air filtration and lower ventilation rates. One important reason for the lower ventilation rates in these classrooms is that the rooms become excessively cooled by the supply of outdoor air with low temperature (this investigation was conducted during the heating season in Sweden). Thus, the ventilation rate needs to be kept low in order to avoid uncomfortably low indoor temperatures and draught. Consequently, windows are kept closed more than motivated by air quality.

Our results showed no significant differences in indoor air quality between classrooms with the simpler balanced mechanical ventilation system with constant air flow rates and those demand controlled with variable air flow rate. This is actually the expected result since the main reason for installing demand-controlled ventilation is to save energy (electricity for fan operation and energy for heating - and sometimes cooling - of the supply air), not to improve indoor air quality. Instead of running the ventilation system at nominal capacity the entire workday regardless of the occupancy, the ventilation is reduced when there is no need for it. A demand-controlled ventilation system reduces the ventilation rate to a minimum when the temperature and the concentration of CO_2 are low (i.e., when there is no demand). Our results indicate that the periodically reduced ventilation rates in the studied demand-controlled ventilation systems do not deteriorate the quality of the indoor air during times of occupancy.

Based on the results, ACR appears to be a good proxy for indoor air quality. Higher ACRs are associated with lower CO_2 and the gaseous indoor air pollutants such as the carcinogenic formaldehyde and VOCs. Lower levels of CO_2 and VOCs are associated with improved cognitive function scores [59]. Therefore, achieving sufficiently high ACRs is confirmed to be important for children's performance at school.

Balanced mechanical ventilation systems with heat recovery are installed in many schools in Sweden which is not a case in many other countries. In addition, there is a requirement for all newly constructed school buildings to be equipped with demand-controlled ventilation, i.e. mechanical ventilation systems with variable air volume. However, the differences in IAQ among ventilation strategies have not been previously studied so comprehensively in Sweden. The findings from this work can be generalized to other schools and contribute with useful knowledge to other countries heading towards the same direction with respect to school ventilation.

5. Conclusions

The IAQ in the studied Swedish classrooms was, at median level, good regardless of their ventilation system. The concentrations of ozone, formaldehyde and TVOC in the majority of classrooms were below recommended guideline values. On the contrary, the concentrations of NO_2, PM_{10} and $PM_{2.5}$ exceeded the latest WHO guideline [26] values in 47%, 22% and 73%, respectively. All classrooms with natural or exhaust ventilation and approximately 50% of the classrooms with balanced mechanical ventilation did not comply with the Swedish ventilation requirements. However, the results represent only one school week of measurements. Long-term measurements should confirm the findings.

The three ventilations systems performed equally well in providing comfortable thermal environment. The main difference in indoor air quality was observed between natural and balanced mechanical ventilation. Classrooms with natural and exhaust ventilation or automated window opening had significantly lower air change rates, higher concentrations of CO_2, formaldehyde, PM_{10} and $PM_{2.5}$, and poorer IAQ indicated by the aggregated Indoor Air Pollution Index, than classrooms with balanced mechanical ventilation with heat recovery and particle filtration. The balanced mechanical ventilation systems with variable air volume (VAV) did not perform significantly better regarding IAQ than the systems with constant air volume (CAV). The main differences between CAV and VAV systems include energy consumption for fan electricity, operational requirements and maintenance. These aspects should also be considered when choosing ventilation strategy.

Funding statement

Formas – Swedish Research Council for Sustainable Development, Grant number 2017-01015.

CRediT authorship contribution statement

Blanka Cabovská: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis. **Gabriel Bekö:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis. **Despoina Teli:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Lars Ekberg:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis. **Jan-Olof Dalenbäck:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Pawel Wargocki:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Theofanis Psomas:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Sarka Langer:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available in Supporting information file.

Acknowledgements

The study was funded by Formas – the Swedish Research Council for Sustainable Development (Grant Number 2017-01015). We thank Maria Alm and Jan-Erik Andersson from Lokalförvaltningen, the municipal property manager of primary schools in Gothenburg, for their help with the selection of the school buildings and for practical arrangements with access to the schools. We are grateful to the principals, teachers and children for participation in our study. Erik Svensson from the Environment Administration Office of the City of Gothenburg kindly provided ambient air quality data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109744.

References

[1] P.J. Landrigan, C.A. Kimme, A. Correa, B. Eskenazi, Children's health and the environment: Public health issues and challenges for risk assessment, Environ. Health Perspect. 112 (2004) 257–265. https://doi:10.1289/ehp.6115.

[2] Z.S. Zomorodian, M. Tahsildoost, M. Hafezi, Thermal comfort in educational buildings: a review article, Renew. Sustain. Energy Rev. 59 (2016) 895–906, https://doi.org/10.1016/j.rser.2016.01.033.

[3] P. Wolkoff, Indoor air humidity, air quality, and health – an overview, Int. J. Hyg Environ. Health 221 (2018) 376–390, https://doi.org/10.1016/j.ijheh.2018.01.015.

[4] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, The relationship between classroom temperature and children's performance in school, Build. Environ. 157 (2019) 197–204, https://doi.org/10.1016/j.buildenv.2019.04.046.

[5] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, W. Bahnfleth, The relationships between classroom air quality and children's performance in school, Build. Environ. 173 (2020), 106749, https://doi.org/10.1016/j.buildenv.2020.106749.

[6] W.J. Fisk, The ventilation problem in schools: literature review, Indoor Air 27 (2017) 1039–1051, https://doi.org/10.1111/ina.12403.

[7] U. Haverinen-Shaughnessy, R.J. Shaughnessy, E.C. Cole, O. Toyinbo, D. J. Moschandreas, An assessment of indoor environmental quality in schools and its association with health and performance, Build. Environ. 93 (2015) 5–40, https://doi.org/10.1016/j.buildenv.2015.03.006.

[8] J.M. Daisey, W.J. Angell, M.G. Apte, Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information, Indoor Air 13 (2003) 53–64, https://doi.org/10.1034/j.1600-0668.2003.00153.x.

[9] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, Indoor Air 15 (2005) 27–52, https://doi.org/10.1111/j.1600-0668.2004.00320.x.

[10] Public Health Agency of Sweden, Indoor environment in schools – a supervision project 2014-2015 (in Swedish: Inomhusmiljön i skolan - Ett nationellt tillsynsprojekt 2014–2015, https://www.folkhalsomyndigheten.se/contentassets/f7ebb232fe774aada7c18e7847530345/inomhusmiljon-skolan-15128-webb.pdf. (Accessed 31 May 2022).

[11] ANSI/ASHRAE Standard 62.1-2019. Ventilation for Acceptable Indoor Air Quality. ASHRAE Atlanta, GA 30329, USA.

[12] SS-EN 16798-1, Energy Performance of Buildings – Ventilation for Buildings – Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics – Module M1-6, SIS, Swedish Standards Institute, Stockholm, Sweden, 2019.

[13] (in Swedish), Rules for Building BBR 20. BSF 2013:14, Boverket - Swedish National Board of Housing, Building and Planning, 2013.

[14] L.C. Renaud-Salis, O. Ramalho, M. Abadie, Towards the definition of an indoor air quality index for residential buildings based on long-and short-term exposure limit values, Int. J. Vent. 19 (2020) 189–200. https://www.tandfonline.com/loi/tjov20.

[15] J. A Becerra, J. Lizana, M. Gil M, A. Barrios-Padura, P. Blondeau, R. Chacartegui, Identification of potential indoor air pollutants in schools, J. Clean. Prod. 242 (2020), 118420, https://doi.org/10.1016/j.jclepro.2019.118420.

[16] N. Canha, C. Mandin, O. Ramalho, G. Wyart, J. Ribéron, C. Dassonville, O. Hänninen, S.M. Almeida, M. Derbez, Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France, Indoor Air 26 (2016) 350–365, https://doi.org/10.1111/ina.12222.

[17] K.K. Kalimeri, D.E. Saraga, V.D. Lazaridis, N.A. Legkas, D.A. Missia, E.I. Tolis, J. G. Bartzis, Indoor air quality investigation of the school environment and estimated health risks: two-season measurements in primary schools in Kozani, Greece, Atmos, Pollut. Res. 7 (2016) 1128–1142, https://doi.org/10.1016/j.apr.2016.07.002.

[18] B. Simanic, B. Nordquist, H. Bagge, D. Johansson, Indoor air temperatures, CO$_2$ concentrations and ventilation rates: long-term measurements in newly built low-energy schools in Sweden, J. Build. Eng. 25 (2019), 100827, https://doi.org/10.1016/j.jobe.2019.100827.

[19] E. Oldham, H. Kim, IEQ field investigation in high-performance, urban elementary schools, Atmosphere 11 (2020) 81, https://doi.org/10.3390/atmos11010081.

[20] O. Ramalho, C. Mandin, J. Ribéron, G. Wyart, Air stuffiness and air exchange rate in French schools and day-care centres, Int. J. Vent. 12 (2013) 175–180, https://doi.org/10.1080/14733315.2013.11684013.

[21] O. Ramalho, G. Wyart, C. Mandin, P. Blondeau, P.-A. Cabanes, N. Leclerc, J.-U. Mullot, J. Boulanger, M. Redaelli, Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values, Build. Environ. 93 (2015) 115–124, https://doi.org/10.1016/j.buildenv.2015.03.018.

[22] T. Salthammer, E. Uhde, T. Schripp, A. Schieweck, L. Morawska, M. Mazaheri, S. Clifford, C. He, G. Buonanno, X. Querol, M. Viana, P. Kumar, Childrens' well-being at schools: impact of climatic conditions and air pollution, Environ. Int. 94 (2016) 196–210, https://doi.org/10.1016/j.envint.2016.05.009.

[23] WHO, World Health Organization. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005, Summ. Risk Assess. (2005). https://www.euro.who.int/_data/assets/pdf_file/0008/147851/E87950.pdf. (Accessed 31 May 2022).

[24] WHO, WHO Guidelines for Indoor Air Quality: Selected Pollutants, World Health Organization, 2010. WHO Regional Office for Europe, https://www.euro.who.int/_data/assets/pdf_file/0009/128169/e94535.pdf. (Accessed 31 May 2022). accessed.

[25] H. Fromme, M. Debiak, H. Sagunski, C. Röhl, M. Kraft, M. Kolossa-Gehring, The German approach to regulate indoor air contaminants, Int. J. Hyg Environ. Health 222 (2019) 347–354, https://doi.org/10.1016/j.ijheh.2018.12.012.

[26] WHO, 2021. World Health Organization, WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide, 2021. https://apps.who.int/iris/handle/10665/345329. (Accessed 31 May 2022).

[27] H. Salonen, T. Salthammer, L. Morawska, Human exposure to NO$_2$ in school and office indoor environment, Environ. Int. 130 (2019), 104887, https://doi.org/10.1016/j.envint.2019.05.081.

[28] H. Salonen, T. Salthammer, L. Morawska, Human exposure to ozone in school and office indoor environments, Environ. Int. 119 (2018) 503–514, https://doi.org/10.1016/j.envint.2018.07.012.

[29] A. Morawska, Afshari, G.N. Bae, G. Buonanno, C.Y.H. Chao, O. Hänninen, W. Hofmann, C. Isaxon, E.R. Jayaratne, P. Pasanen, T. Salthammer, M. Waring, A. Wierzbicka, Indoor aerosols: from personal exposure to risk assessment, Indoor Air 23 (2013) 462–487, https://doi.org/10.1111/ina.12044.

[30] L. Morawska, G.A. Ayoko, G.N. Bae, G. Buonanno, C.Y.H. Chao, S. Clifford, S.C. Fu, O. Hänninen, C. He, C. Isaxon, M. Mazaheri, T. Salthammer, M.S. Waring, A. Wierzbicka, Airborne particles in indoor environment of homes, schools, offices and aged care facilities: the main routes of exposure, Environ. Int. 108 (2017) 75–83, https://doi.org/10.1016/j.envint.2017.07.025.

[31] U. Haverinen-Shaughnessy, D.J. Moschandreas, R.J. Shaughnessy, Association between substandard classroom ventilation rates and students' academic achievement, Indoor Air 21 (2011) 121-131, https://doi.org/10.1111/j.1600-0668.2010.00686.x.

[32] P.T.B.S. Branco, M.C.M. Alvim-Ferraz, F.G. Martins, S.I.V. Sousa, Quantifying indoor air quality determinants in urban and rural nursery and primary schools, Environ. Res. 176 (2019), 108534, https://doi.org/10.1016/j.envres.2019.108534.

[33] M. Szabados, Z. Csákó, B. Kotlík, H. Kazmarová, A. Kozajda, A. Jutraz, A. Kukec, P. Otorepec, A. Dongiovanni, A. Di Maggio, S. Fraire, T. Szigeti, Indoor air quality and the associated health risk in primary school buildings in Central Europe –The InAirQ study, Indoor Air 31 (2021) 989–1003, https://doi.org/10.1111/ina.12802.

[34] R.M. Baloch, C.N. Maesano, J. Christoffersen, S. Banerjee, M. Gabriel, É. Csobod, E. de Oliveira Fernandes, I. Isabella Annesi-Maesano, Indoor air pollution, physical and comfort parameters related to schoolchildren's health: data from the European SINPHONIE study, Sci. Total Environ. 739 (2020), 139870, https://doi.org/10.1016/j.scitotenv.2020.139870.

[35] F. Villanueva A. Tapia, S- Lara, M. Amo-Salas, Indoor and outdoor air concentrations of volatile organic compounds and NO$_2$ in schools of urban, industrial and rural areas in Central-Southern Spain, Sci. Total Environ. (2018) 622–623, https://doi.org/10.1016/j.scitotenv.2017.11.274, 222–235.

[36] M. Turunen, O. Toyinbo, T. Putus, A. Nevalainen, R. Shaughnessy, U. Haverinen-Shaughnessy, Indoor environmental quality in school buildings, and the health and wellbeing of students, Int. J. Hyg Environ. Health 217 (2014) 733–739, https://doi.org/10.1016/j.ijheh.2014.03.002.

[37] Y.-H. Mi, D. Norbäck, J. Tao, Y.-L. Mi, M. Ferm, Current asthma and respiratory symptoms among pupils in Shanghai, China: influence of building ventilation, nitrogen dioxide, ozone, and formaldehyde in classrooms, Indoor Air 16 (2006) 454–464, https://doi.org/10.1111/j.1600-0668.2006.00439.x.

[38] AFS 2020:1. Arbetsmiljöverket (the Swedish work environment authority) 2020. Workplace design (in Swedish: arbetsplatsens utformning), Stockholm, Sweden, https://www.av.se/arbetsmiljoarbete-och-inspektioner/publikationer/foreskrifter/arbetsplatsens-utformning-afs-20201-foreskrifter/. (Accessed 31 May 2022).

[39] REHVA Guidebook No 11, Air Filtration in HVAC Systems, Federation of European Heating and Air-conditioning Associations, 2020. https://www.rehva.eu/knowledge-base/rehva-guidebook-11. (Accessed 31 May 2022). accessed.

[40] City of Gothenburg: open data, Available on-line: https://goteborg.se/wps/portal/start/kommun-o-politik/kommunfakta/digitalisering/oppna-data/oppna-data-soksida. (Accessed 2 August 2022). accessed.

[41] State of the climate in 2021, in: J. Blunden, T. Boyer (Eds.), Special Supplement to the Bulletin of the American Meteorological Society 103 (2022), https://doi.org/10.1175/2022BAMSStateoftheClimate.1. Si–S465.

[42] ASTM Standard E741-11, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution, 2019, https://doi.org/10.1520/E0741-11R17.

[43] M. Ferm, H. Rodhe, Measurements of air concentrations of SO$_2$, NO$_2$ and NH$_3$ at rural and remote sites in Asia, J. Atmos. Chem. 27 (1997) 17–29, https://doi.org/10.1023/A:1005816621522.

[44] ISO 16000-4., Indoor air e part 4: determination of formaldehyde e diffusive sampling method, International Organization of Standardization, Geneva, 2004.

[45] ISO 16017-2., Indoor, ambient and workplace air e sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary as chromatography e Part 2: diffusive sampling, International Organization of Standardization, Geneva, 2003.

[46] D.J. Moschandreas, S.C. Sofuoglu, The Indoor Environmental Index and its relationship with symptoms of office buildings occupants, J. Air Waste Manage. Assoc. 54 (2004) 1440–1451, https://doi.org/10.1080/10473289.2004.10470999.

[47] Public Health Agency's general advice on indoor temperature (in Swedish: Allmänna råd om temperatur inomhus), FoHMFS 2014:17. Folkhälsomyndigheten, Public Health Agency of Sweden), Stockholm, Sweden, 2014, https://www.folkhalsomyndigheten.se/publicerat-material/publikationsarkiv/f/fohmfs-201417/. (Accessed 31 May 2022).

[48] S. Deng, J. Lau, Seasonal variations of indoor air quality and thermal conditions and their correlations in 220 classrooms in the Midwestern United States, Build, Environ. Times 157 (2019) 79–88, https://doi.org/10.1016/j.buildenv.2019.04.038.

[49] The Swedish Public Health Agency's general advice about ventilation (in Swedish: Folkhälsomyndighetens allmänna råd om ventilation), FoHMFS 2014:18. Folkhälsomyndigheten, Public Health Agency of Sweden), Stockholm, Sweden,

2014. Folkhälsomyndigheten, https://www.folkhalsomyndigheten.se/publicerat-material/publikationsarkiv/f/fohmfs-201418/. (Accessed 31 May 2022).

[50] A. Persily, L. de Jonge, Carbon dioxide generation rates for building occupants, Indoor Air 27 (2017) 868–879, https://doi.org/10.1111/ina.12383.

[51] J. Pejtersen, G. Clausen, J. Sørensen, D. Quistgaard, G. Iwashita, Y. Zhang, T. Onishi, P.O. Fanger, Air pollution sources in kindergartens, Proceedings of IAQ 91 Healthy Buildings 91 (1991) 221–224. Washington DC, USA.

[52] M. Sakamoto, M. Li, K. Kuga, K. Ito, G. Bekö, J. Williams, P. Wargocki, CO_2 emission rates from sedentary subjects under controlled laboratory conditions, Build. Environ. 211 (2022), 108735, https://doi.org/10.1016/j.buildenv.2021.108735.

[53] Y. Hu, B. Zhao, Relationship between indoor and outdoor NO_2: a review, Build. Environ. 180 (2020), 106909, https://doi.org/10.1016/j.buildenv.2020.106909.

[54] K.K. Kalimeri, J.G. Bartzis, I.A. Sakellaris, E. de Oliveira Fernandes, Investigation of the $PM_{2.5}$, NO_2 and O_3 I/O ratios for office and school microenvironments, Environ. Res. 179 (2019), 108791, https://doi.org/10.1016/j.envres.2019.108791.

[55] C. Weschler, Ozone in indoor environments: concentration and chemistry, Indoor Air 10 (2000) 269–288, https://doi.org/10.1034/j.1600-0668.2000.010004269.x.

[56] W.W. Nazaroff, C.J. Weschler, Indoor ozone: concentrations and influencing factors, Indoor Air 32 (2022), e12942, https://doi.org/10.1111/ina.12942.

[57] H. Fromme, T. Lahrz, R. Burkhardt, L. Fembacher, M. Kraft, S. Sievering, D. Kadler, S. Dietrich, Luftkvalität in Kindertagesstätten (Indoor air quality in German daycare centers), Gefahrst. Reinhalt. Luft 76 (2016) 55–61.

[58] Public Health England, Indoor Air Quality Guidelines for Selected Volatile Organic Compounds (VOCs) in the UK, Published September, 2019. Available on-line: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831319/VO_statement_Final_12092019_CS__1_.pdf. (Accessed 2 August 2022).

[59] J.G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, J.D. Spengler, Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments, Environ. Health Perspect. 124 (2016), https://doi.org/10.1289/ehp.1510037, 805-712.