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Article

Effects of Night Ventilation on Indoor Air Quality in Educational Buildings—A Field Study

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Featured Application: The study provides insights into the mechanical night ventilation methods used in unoccupied hours while improving indoor air quality at the beginning of occupied hours in educational buildings.

Abstract: Night ventilation methods have been used in educational buildings to guarantee indoor air quality at the beginning of occupied periods. A typical method has been to pre-start ventilation 2 h before the space usage. Another selection has been to ventilate a building continuously during the night with a minimum airflow rate that can dilute material emissions. In this study, the pre-started, continuous, and intermittent ventilation methods were compared by assessing indoor air quality in field measurements. The daytime ventilation was operating normally. The test periods lasted for 2 weeks. Indoor air quality was assessed by measuring the total volatile organic compounds and microbial concentrations using the quantitative polymerase chain reaction method. Additionally, the thermal conditions, carbon dioxide, and pressure differences over the building envelope were measured. The results show that the night ventilation strategy had negligible effects on microbial concentrations. In most cases, the indoor air microbial concentrations were only a few percent of those found outdoors. The averaged concentration of total volatile organic compounds was at the same level with all the night ventilation methods at the beginning of the occupied periods in the mornings. The concentrations reached a minimum level after 2-h ventilation. The concentrations of total volatile organic compounds were higher during the day than at night. This reveals that space usage had the largest effect on the total volatile organic compounds. Generally, the results show that continuous night ventilation does not significantly affect the biological and chemical contaminants. Consequently, a 2-h flushing period is long enough to freshen indoor air before occupancy.

Keywords: intermittent ventilation; night purging; indoor air quality; TVOC; microbes

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1. Introduction

Ventilation plays an important role in supporting wellbeing indoors [1–3]. Research literature has shown that poor ventilation is usual in schools, worsening the health symptoms of individuals [3–6]. Furthermore, poor indoor air quality may have a significant influence on learning [7–9]. However, taking care of health and wellbeing has caused additional ventilation use which rises the energy consumption of buildings. The European standard 15251:2007 recommends using pre-started or continuous minimum ventilation in unoccupied hours to remove material emissions before space usage [10]. In Nordic countries, a usual method has been to stop mechanical ventilation after the building usage and pre-start the ventilation around 2 h before the occupied periods. An alternative ventilation method has been to use night ventilation at 30–50% partial power that can remove material emissions. A third method has been to use intermittent ventilation during unoccupied periods, and in this way, achieve a minimum night-time ventilation level in spaces on average.

In earlier studies, Montgomery et al. [11] discussed that increased TVOC concentration in the mornings may occur due to off-gassing of building materials because the ventilation is not used at night. Hunt and Kaye [12] concluded that a required purging rate of pollutants is closely related to the air distribution methods, prevailing buoyancy forces, as well as room size. In schools, a usual method has been to flush indoor air through the windows or doors after lectures [13–15]. Chao and Hu [16] discussed that classroom occupants can be exposed to harmful concentrations because emissions may accumulate without proper ventilation during the unoccupied periods. Earlier research shows that night ventilation has been typically used to enhance indoor thermal conditions [17–22]. Even though many standards and guidelines have been provided for health-based ventilation [10,23,24], different night ventilation methods have been relatively rarely studied regarding organic pollutant levels in the mornings at the beginning of space use.

Many hypotheses have been proposed on how indoor environments deteriorate during unoccupied hours without continuous ventilation. The first hypothesis states that by stopping the ventilation, harmful concentrations can increase in indoor air during unoccupied hours, and at the same time, may affect the daytime concentrations. In this sense, the flushing period is required also after the space usage. The second hypothesis is the concern that the indoor humidity cannot be extracted if the ventilation is off. The third hypothesis is that the start-up of ventilation will increase the concentrations of particulate matter in the morning. Continuous ventilation can be thought of as a solution to these problems, but at the same time, it can unnecessarily increase the energy consumption related to the management of indoor climate conditions.

CO_2 usually indicates human-originated bio emissions in indoor environments. However, the material or biological emissions can be originated also from many other indoor and outdoor sources. Generally, organic and microbial metabolites may have considerable effects on health, but it is difficult to show which compounds are responsible for causing diseases and symptoms [25]. For this reason, a general trend of volatile organic compounds (VOCs) was monitored by measuring a total amount of those compounds (TVOC) by conducting the metal oxide semiconductor method. This means however that the individual VOCs cannot be identified. Regardless of that, it has been shown that TVOC can be a reasonable indicator for indoor material emissions [26–28]. In addition to TVOC, particulate matter (PM) is a common harmful contaminant of indoor environments. Particulate matter is defined as a widespread air pollutant, consisting of a mixture of solid and liquid particles suspended in the air [29]. PM2.5 and PM10 concentration levels have been usually discovered, that is the pollutants of a diameter of less than 2.5 and 10 μm, respectively. It has been estimated that PM2.5 constitutes 50–70% of outdoor PM10 in many European regions [29].

In indoor air, occupants are exposed daily to different microbes. Therefore, it is relevant to assess their concentrations and temporal growth in indoor environments. In many studies, so-called surrogate methods have been used while investigating indoor microbial exposure [30–33]. Leppänen et al. [34] proposed that a settled dust method can be a reasonable method, reflecting well the microbial compositions and environmental determinants. The authors compared different methods and showed sampling strategies for the quantitative assessment. The general characteristics of microbial flora can be estimated by identifying large groups of microbial species. The commonly explored groups measured in this study are total fungal content (Unifung) [35], the group of *Penicillium*, *Aspergillus*, and *Paecilomyces variotii* (Pen/Asp) [36], as well as the Gram-positive (Grampos) and the Gram-negative (Gramneg) bacteria groups [37].

Haugland et al. [36] showed that generic assay corresponds rather well the sum of individual assays. Kärkkäinen et al. [37] compared qPCR methods in determining a bacterial load in dust samples. The authors concluded that different methods represent different aspects of bacterial exposure and, as a consequence, those results may slightly have different characteristics. Adams et al. [33] conducted the settled airborne dust as a surrogate for indoor exposure. The authors used plastic petri dishes and analyzed the samples with the qPCR method in quantifying a total bacterial and fungal biomass. Their finding was that petri dishes are an inexpensive, simple, and feasible method, meeting the requirements of passive sampling approaches.

In this study, the knowledge cap is related to how different unoccupied ventilation strategies affect PM, TVOC, and microbial concentrations immediately in the morning and also during the occupied period. Consequently, the pre-started, continuous, and intermittent night ventilation methods were compared during the unoccupied hours. The study objects were selected among educational buildings without any recognized indoor air quality or thermal problems. The spaces were used and ventilated normally during occupied hours. The objective of the study was to provide insight into the night ventilation usage for building owners in educational buildings, and thus to optimize night ventilation usage without increasing unnecessary energy consumption. The novelty of the study is the analysis of the effects of night ventilation methods on indoor air quality at the beginning of the occupied hours. In addition, the microbial levels were measured during each test period to assess long-term cumulative exposure to microbes using the night ventilation methods.

2. Materials and Methods

The measurements were carried out in 11 educational buildings. The measured buildings included 6 schools and 5 kindergartens in southern Finland (Figure 1). The buildings were measured in different seasons. The buildings had variable air volume (VAV) and constant air volume (CAV) mixing ventilation systems. The buildings were used and ventilated normally during the occupied periods. The pre-started, continuous, and intermittent ventilation was used during the unoccupied hours. The thrown pattern with all ventilation strategies was tested before the measurement campaign. Thus, the ventilation efficiency of the tests conducted was almost the same in all test conditions.

2.1. Measured School Buildings

Primary school 1 was built in 2013. The measured classroom (40 m^2) had a nozzle duct variable air volume (VAV) mixing ventilation system at the ceiling zone (Figure 1a). The exhaust grille was at the corridor wall bulkhead. The ventilation was operated at partial power in unoccupied hours, corresponding to a ventilation rate of 85 L/s while the maximum rate was 120 L/s. The number of occupants was typically 10–20 individuals. The set value of indoor air temperature was 21 °C and the set values of CO_2 were 700 and 900 ppm, whereby the ventilation gradually increased from the partial power of 50% to maximum power of 100%, respectively.

Primary school 2 was built in 2006 and there were also renovations in 2012. The measured classroom (65 m^2) had a constant air volume (CAV) mixing ventilation system (Figure 1b) with the air distribution from the ceiling terminal devices. The exhaust air grilles were also at the ceiling. In the CAV system, the operation of air handling units was controlled by the defined time program in the building automation system. Furthermore, the system maintained a constant static pressure in ductwork with frequency converter-driven fan motors. The control setting was either fast (1/1), slow (1/2), or stop. The design airflow rate was 190 L/s which is around 3 L/s·m^2, and 7.5 L/s per person for 25 individuals.

Figure 1. Measured indoor environments: (**a**) classroom in primary school 1 in winter; (**b**) classroom in primary school 2 in autumn; (**c**) classroom in primary school 3 in spring; (**d**) classroom in primary school 4 in autumn; (**e**) classroom in secondary school in autumn; (**f**) group workspace in university building in spring; (**g**) playroom in kindergarten 1 in winter; (**h**) playroom in kindergarten 2 in autumn; (**i**) playroom in kindergarten 3 in summer; (**j**) playroom in kindergarten 4 in late autumn; (**k**) playroom in kindergarten 5 in summer; (**l**) measuring instruments.

Primary school 3 was built in 1953 and was renovated in 2012. The classroom (60 m^2) had a corridor wall grille CAV mixing air distribution system (Figure 1c). The exhaust air valves were at the ceiling on the other side of the room. The control setting was either fast (1/1), slow (1/2), or stop. The design airflow rate was 180 L/s which is around 3 L/s·m^2, and 6.4 L/s per person for 28 individuals.

Primary school 4 was built in 2012. The classroom (87.5 m^2) had a nozzle duct VAV mixing air distribution system at the ceiling zone (Figure 1d) that was controlled with CO_2, air temperature, and occupancy sensor. The exhaust air valves were at the ceiling zone on the other side of the room. The ventilation system was also used for heating. The designed maximum occupied airflow was 305 L/s which is 3.5 L/s·m^2 for 20–30 individuals. The minimum occupied airflow was 92 L/s and the unoccupied airflow was 44 L/s, which is 14% from the maximum.

The secondary school was built in 1975 and renovated in 2014. The classroom (42 m^2) had VAV mixing ventilation (Figure 1e) from the air distribution of a perforated duct diffuser located above the occupied zone. The exhaust air grille was on the corridor wall at the ceiling zone. The ventilation system was controlled by the air temperature and CO_2. The minimum set value for indoor air temperature was 21 °C. The maximum set value for CO_2 was 650 ppm after which the ventilation increased gradually from 20% to 100%. The designed maximum occupied airflow was 150 L/s for 25 persons (6 L/s per person) which is about 3.6 L/s·m^2.

The university building was built in 1964 and renovated in 2015. The group workspace (39.5 m^2) had a VAV corridor wall grille mixing diffuser air distribution system (Figure 1f). The exhaust grilles were at the corridor wall as well. The ventilation system maintained constant static pressure in the ductwork and the airflow rate is boosted by the open on-off damper. The control parameters were air temperature, CO_2, and boost button on the wall.

The normal occupied airflow rate was 80 L/s which is around 2 L/s·m^2 for 3–5 individuals whereas the maximum airflow rate was 160 L/s.

Table 1 shows the specific characteristics of indoor environments, test cases, and time program of ventilation systems. In primary school 4, the pre-started night ventilation method could not be tested, because their normal strategy was continuous ventilation.

Table 1. The measured school buildings: occ denotes the usual number of occupants in the room, floor refers to the floor area in the room, CAVmax is the maximum airflow rate per floor square meter in a constant air volume system, and VAVmax is the corresponding airflow in a variable air volume system.

Primary School 1	**Ventilation (VAV)**	**Weekdays**	**Weekend**
built: 2013	pre-started	mon 04–18, tue-fri 05–18	1 h per day
VAVmax.: 3 L/s·m^2	continuous	00–24	00–24
floor: 40 m^2, occ: 10–20	intermittent	as in case 1 + 20–22 + 00–02	02–05 + 10–13 + 18–21
Primary School 2	**Ventilation (CAV)**	**Weekdays**	**Weekend**
built: 2006, renov: 2012 CAVmax.: 3 L/s·m^2	pre-started	mon 05–18, tue-fri 06–18	14–15
floor: 65 m^2	continuous	00–24	00–24
occ: 20–30 person	intermittent	as in case 1 + 20–22 + 01–03	02–05 + 10–13 + 18–21
Primary School 3	**Ventilation (CAV)**	**Weekdays**	**Weekend**
built: 1953, renov: 2012 CAVmax: 3 L/s·m^2	pre-started	mon-tue 05:30–20:00, wed-fri 05:30–18:00	06:00–18:00
floor: 60 m^2	continuous max	00–24	00–24
occ: 20–30 person	continuous min	as in case 1 + half power at night	as in case 1 + half power at night
Primary School 4	**Ventilation (VAV)**	**Weekdays**	**Weekend**
built: 2012	continuous	00–24	00–24
VAVmax: 3.5 L/s·m^2 floor: 87.5 m^2, occ: 20–30	intermittent	05–18 + 20–22 + 01–03, otherwise minimum	02–05 + 10–13 + 18–21, otherwise minimum
Secondary School	**Ventilation (VAV)**	**Weekdays**	**Weekend**
built: 1975, renov: 2014,	pre-started	mon 05–17 tue-fri 06–17	-
VAVmax: 3.6 L/s·m^2	continuous max	00–24, max at night	00–24, max
floor: 42 m^2, occ: 20–25	continuous min	00–24, min at night	00–24, min
University Building	**Ventilation (VAV)**	**Weekdays**	**Weekend**
built: 1964, renov: 2015,	pre-started	06–17	-
VAVmax: 4 L/s·m^2	continuous	00–24	00–24
floor: 39.5 m^2, occ: 3–5	intermittent	06–17 + 19–21 + 02–04	02–05 + 10–13 + 18–21

2.2. Measured Kindergartens

Kindergarten 1 was built in 2015. The playroom (37 m^2) had a CAV mixing ventilation system at a corridor bulkhead (Figure 1g). The set values for the supply air temperature were from 22 to 17 °C and corresponded to the set values for the exhaust air temperature from 20 to 25 °C, respectively. The time program controlled the air handling units. The designed supply airflow rate was 110 L/s which was 3 L/s·m^2 for the 10–20 individuals.

Kindergarten 2 was built in 2003. The playroom (30 m^2) had a corridor bulkhead CAV air distribution system (Figure 1h) with cascade control of the supply air temperature based on the exhaust air temperature. The air handling units in the other service areas had a shorter operating time than in the playroom. The designed supply airflow rate was 105 L/s which was 3.5 L/s·m^2 for 5–15 individuals.

Kindergarten 3 was built in 2012. The playroom (21 m^2) had a corridor bulkhead CAV mixing air distribution system (Figure 1i). The system maintains constant static pressure in ductwork with frequency converter-driven fan motors and supply air temperature cascade control with room sensors. The control setting was either fast (1/1), slow (1/2), or stop. The exhaust air valves were at the corridor wall. The designed ventilation rate was 3 L/s·m^2. The playroom was for 5–10 children.

Kindergarten 4 was built in 2013. The playroom (34 m^2) had a VAV ceiling mixing air distribution system (Figure 1j) which was controlled with CO_2, air temperature, and occupancy sensors. The exhaust air grille was at the ceiling. The measured airflow rate for the unoccupied room was 50 L/s which is 1.5 L/s·m^2. The playroom was made for 10–15 children.

Kindergarten 5 was built in 2014. The playroom (36 m^2) had a VAV wall grille mixing air distribution system (Figure 1k) which was controlled with CO_2, air temperature, and occupancy sensors. The exhaust air valves were on the same wall as the supply grilles. The designed maximum airflow rate was 100 L/s which is 2.8 L/s·m^2. The playroom was usually for 5–10 children. The minimum ventilation rate was around 50% of the maximum airflow rate.

Table 2 shows the specific characteristics of indoor environments, test cases, and operating time of ventilation systems. In kindergarten 4 and 5, the pre-started method could not be tested, because their normal strategy was continuous ventilation.

Table 2. The measured kindergartens: occ denotes the usual number of occupants in the room, floor refers to the floor area in the room, CAVmax is the maximum airflow rate per floor square in a constant air volume system, and VAVmax is the corresponding airflow in a variable air volume system.

Kindergarten 1	**Ventilation (CAV)**	**Weekdays**	**Weekend**
built: 2015	pre-started	03:00–17:00	04:00–17:00
CAVmax: 3 L/s·m^2	continuous	00–24	00–24
floor: 37 m^2, occ: 10–20	intermittent	04–20 + 22–01	00–04 + 08–12 + 16–20
Kindergarten 2	**Ventilation (CAV)**	**Weekdays**	**Weekend**
built: 2003 CAVmax: 3.5 L/s·m^2	pre-started	mon 04:30–21:00, tue-fri 05:30–21:00	1 h per day
floor: 30 m^2	continuous	00–24	00–24
occ: 5–15 persons	intermittent	as in case 1 + 01–03	02–05 + 10–13 + 18–21
Kindergarten 3	**Ventilation (CAV)**	**Weekdays**	**Weekend**
built: 2012	pre-started	05–18	-
CAVmax: 3 L/s·m^2	continuous	00–24	00–24
floor: 21 m^2, occ: 5–10	intermittent	05–18 + 20–22 + 01–03	02–05 + 10–13 + 18–21
Kindergarten 4	**Ventilation (VAV)**	**Weekdays**	**Weekend**
2013, 34 m^2, 10–15 prs	continuous	00–24	00–24
unoccupied: 1.5 L/s·m^2	continuous	00–24	00–24
Kindergarten 5	**Ventilation (VAV)**	**Weekdays**	**Weekend**
2014, 36 m^2, 5–10 prs	continuous min	00–24, min at night	00–24, min
VAVmax: 2.8 L/s·m^2	continuous max	00–24, max at night	00–24, max

2.3. *Air Distribution Methods*

Figure 2 shows the air distribution methods in the measured indoor environments. The ventilation systems were mainly mixing ventilation systems. In most cases, the air distribution was implemented from the corridor wall grilles, the ceiling diffusers, or the duct diffusers in the air distribution system. The provided ventilation airflow rates were according to guidelines that were ensured before the test periods.

Figure 2. Typical air distribution methods in measured indoor environments: (**a**) wall air distribution of playroom in kindergarten 2; (**b**) duct air diffuser of classroom in primary school 1; (**c**) wall air distribution of playroom in kindergarten 3; (**d**) duct diffuser of classroom in primary school 4; (**e**) ceiling air distribution of classroom in primary school 2; (**f**) duct diffuser of classroom in secondary school.

2.4. Measurements

The measurements were done for TVOC, particulate matter, and concentration of fungi and bacteria, as well as CO_2 and thermal conditions.

2.4.1. Measuring Instruments

Table 3 shows the measuring instruments. The pressure differences over the building envelope, i.e., over the external wall, were measured by conducting a Sensirion manometer. The manometer sent data to the cloud service at 30-min recording intervals. The air distribution of supply air terminal devices was monitored using either the Sensirion manometer or the Swema 3000 manometer, in which a logging interval was 5 min. The indoor air temperature and CO_2 were measured by conducting the Tinytag loggers that were installed at the height of 1.1 m. The recording interval of Tinytag loggers was 5 min. TVOC measurement was performed by the metal oxide semiconductor method using a Nuvap IEQ monitor that was usually located on a shelf. A sampling was normally 3–4 times per hour.

Table 3. Measuring instruments.

Type	Physical Quantity	Accuracy
Swema 3000	pressure difference	±0.3% ± 0.3 Pa
Sensirion SDP816-125 Pa	pressure difference	±3% ± 0.08 Pa
Tinytag plus 2 TGP-4500	air temperature and humidity	±0.5 °C, ±3.0% RH
Tinytag TGE-0011	CO_2	±3% ± 50 ppm
Nuvap IEQ monitor	TVOC	±15%
Trotec PC220	PM2.5, PM10	±30%, efficiency 50% for 0.3 µm and 100% for >0.45 µm

2.4.2. qPCR-Method for Microbes

Samples of settled dust were collected in 8 adjacent petri dishes from indoor air and outdoor air. The sample dishes were located indoors at a height of 2.0–2.5 m, depending on the shelf height, and outdoors in an open plastic box, usually in a sheltered place. Micro-organisms from the dust samples were determined by quantitative polymerase chain reaction (qPCR method). Gram-positive bacteria were not reported from the outdoor air due to method uncertainty.

At the end of the collection, the plates were sealed with lids and parafilm. In the laboratory, samples were prepared during 7 days after the end of the collection. During sample preparation, each of the plates with lids were carefully swiped into a cotton swab moistened with the dilution solution (sterilized water + 0.05% Tween 20). Each cotton swabs were moved to a tube containing glass beads for DNA isolation. Blanks were always taken every 20 samples; empty petri dishes were treated as well as samples and blanks were analyzed among the samples. Before DNA isolation, samples were stored in a −80 °C freezer.

Dust samples collected in a tube containing glass beads were isolated with a DNA Chemagic DNA plant kit (Perkin Elmer, Ansbach, Germany) according to the manufacturer's instructions using a KingFisher insulation robot (ThermoFisher, Vantaa, Finland). Before DNA isolation, a known concentration of salmon sperm DNA (Sigma-Aldrich, St. Louis, MO, USA) was added to each sample as an internal standard. Samples were milled in a bead mill with glass beads (Sigma Glass beads acid washed 212–300 μm, Sigma-Aldrich) to disrupt microbial cell walls before DNA extraction. DNA was frozen (−20 °C) pending qPCR analyzes.

The samples were determined by the qPCR method (quantitative polymerase chain reaction) using the following assays; the so-called unifung [35], *Penicillium*, *Aspergillus*, and *Paecilomyces variotii* group [36], and Gram-positive and Gram-negative bacteria [37]. Samples were pipetted for qPCR analyzes with a Piro pipetting robot (Dornier, Lindau, Germany) on 96-well optical plates and analyzed on a Stratagene Mx3005P QPCR system (Agilent, Santa Clara, CA, USA). An internal standard was used in the methods salmon sperm DNA analyzed as described previously [38]. In addition, each qPCR assay included positive and negative controls for bacterial and fungal assays to ensure quality. The results were calculated as previously described [36] and the final result is calculated as cell equivalent per square meter per day (CE/m^2·d).

2.4.3. Statistical Analysis

The microbe results were analyzed in SAS Enterprise Guide 8.1. software and graphs were drawn using Origin software. Differences between interventions were analyzed using the Friedman test as well as the Kruskal–Wallis test. The TVOC analysis was made in an Excel-environment as well as all the other analyses.

3. Results

3.1. Microbes

This chapter shows the results of the microbial content of the settled dust, which is classified into the Unifung, Pen/Asp, Grampos, and Gramneg groups. The results support the hypothesis of the effect of night ventilation methods on indoor air quality over a two-week collection period.

3.1.1. Indoor/Outdoor-Ratio

Figure 3 shows the results of microbial groups obtained from microbiological analyzes (qPCR) in the measured indoor environments. As expected, outdoor microbial levels varied with the seasons, with concentrations generally lower in winter due to snow cover. From the concentrations of the settled dust samples, the indoor/outdoor-ratio has been compared for each test case. In most cases, this ratio was in the order of a few percent, i.e., the concentrations were significantly higher outdoors than indoors due to filtration of supply air. The ratio increased only in few buildings above 10% and over 15% ratio in a couple of samples. A good filtration target for mechanical ventilation can be less than 10%. However, indoor activities, filter age, and interior materials affect the results. Therefore, those results are more or less case-specific. At the building level, the ratios are likely to vary significantly due to outdoor and indoor conditions, although daily activity was normal during the measurements. Generally, the ratios were at normal levels and no systematic effects were found between those night-time ventilation strategies.

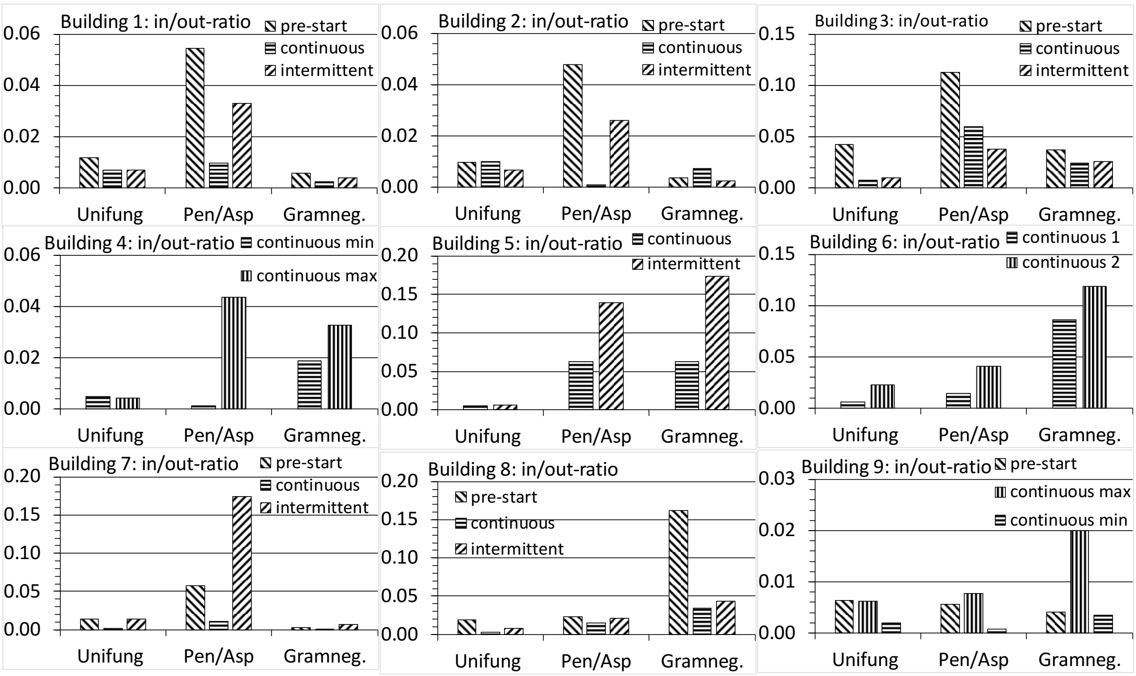

Figure 3. Indoor/outdoor-ratio of the microbial content of the settled dust collected during two weeks. Building 1: group workspace in university building in spring. Building 2: classroom in primary school 3 in spring. Building 3: playroom in kindergarten 3 in summer. Building 4: playroom in kindergarten 5 in summer. Building 5: classroom in primary school 4 in autumn. Building 6: playroom in kindergarten 4 in autumn reflecting natural variation (both test cases are similar). Building 7: classroom in primary school 1 in winter. Building 8: playroom in kindergarten 2 in autumn. Building 9: classroom in secondary school in late autumn.

3.1.2. Indoor Microbial Concentrations

Figure 4 normalizes the indoor microbial concentration in buildings 1–3 with the average CO_2 concentration (mean ± sd), relative humidity, and air temperature measured from a height of 1.1 m. Microbial results are normalized over the pre-started ventilation content to show a change between the test cases. Those results represent an observed trend in the pre-started, continuous, and intermittent night ventilation methods related to space usage, thermal conditions, and humidity levels during each 2-week dust collection period. Generally, the results show that these parameters had no systematic effect on microbial change.

Figure 5 shows box-plot patterns from a comparable sample of objects classified by the microbial group. The sample includes the primary schools 1–2, the kindergartens 1–3, and the university building. In the Unifung group, the mean concentration decreased by 23% and the standard deviation by 21% with the continuous ventilation compared to the pre-started ventilation. Furthermore, the intermittent ventilation decreased the mean unifung content by 37% and the standard deviation by 57% compared to pre-started ventilation. Consequently, the pre-started ventilation increased the total fungal content compared to continuous and intermittent use of night-time ventilation.

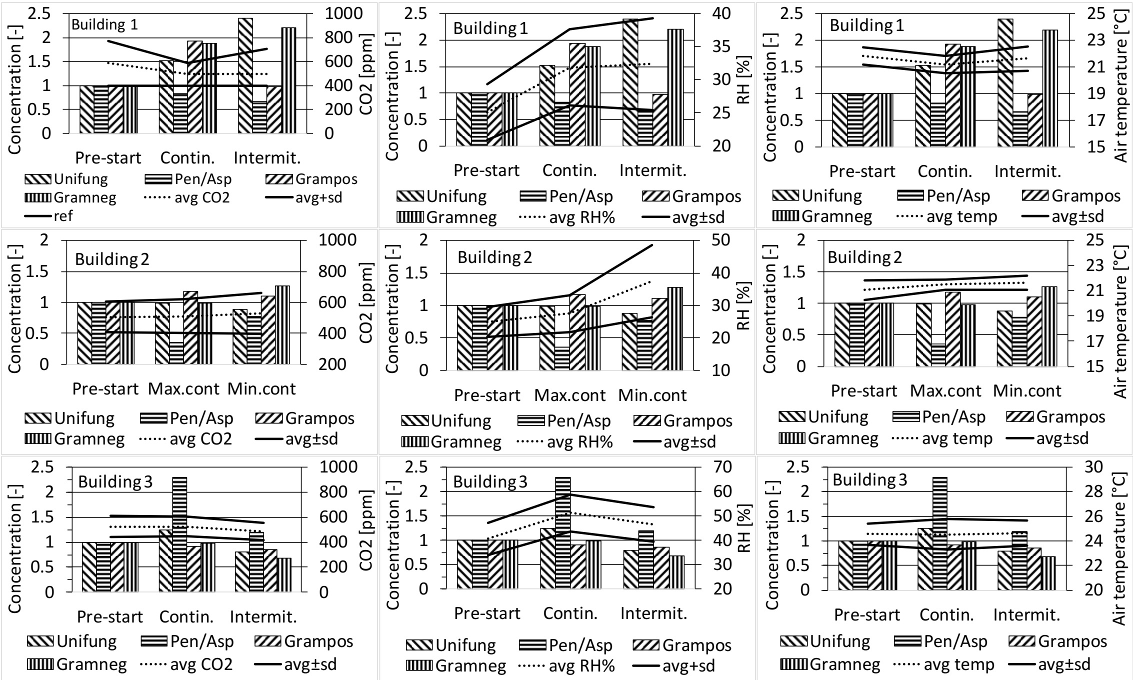

Figure 4. The normalized indoor microbial content [-] related to average CO_2 [ppm], relative humidity [%], and indoor air temperature [°C] classified as microbial group. Building 1 is the university building, building 2 is the primary school 3, and building 3 is the kindergarten 3. CO_2 is the carbon dioxide concentration (avg ± sd), RH is the relative humidity, and temp is the indoor air temperature measured at the height of 1.1 m. The vertical axis on the left is the normalized concentration and the vertical axis on the right is the compared physical quantity, ref is the minimum level, i.e., the background CO_2 level (400 ppm).

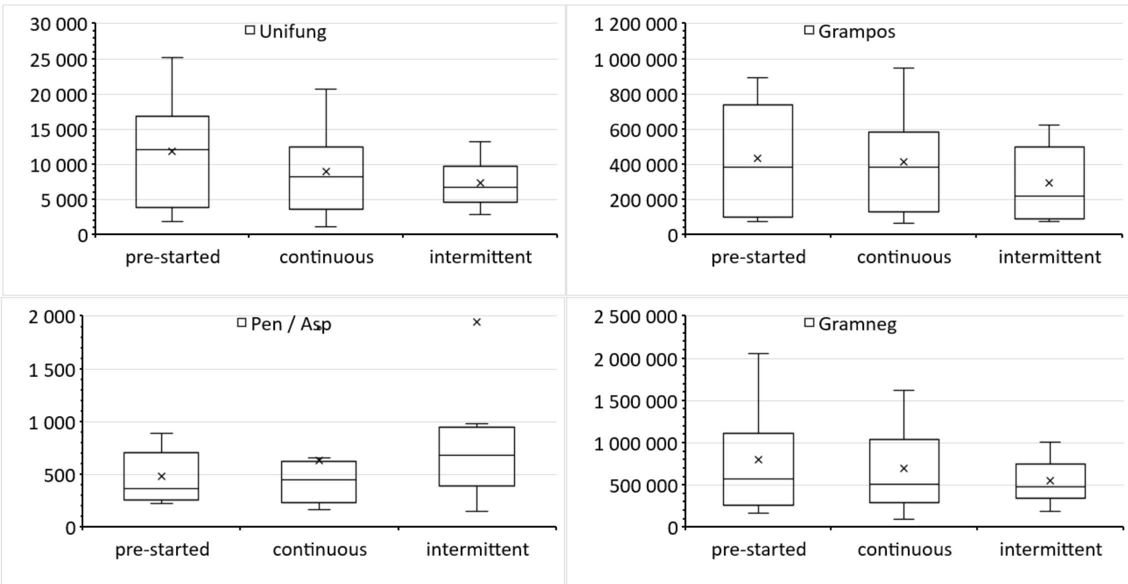

Figure 5. The indoor microbial content [CE/m^2·d] of settled dust collected during two weeks (n = 6). The sample includes the primary schools 1–2, the kindergartens 1–3, and the university building.

In the Pen/Asp group, the lowest mean concentration was observed when the night ventilation was not used at night. One probable reason could be that outdoor air is a typical source of those species, and therefore, the concentration was smaller. Continuous ventilation increased the mean Pen/Asp concentration by 31% and intermittent even multiplied the mean concentration compared to the pre-started ventilation, but the result was affected by one exceptionally large sample. The standard deviation was roughly two times higher with continuous ventilation compared to pre-started ventilation. Hence, the pre-started ventilation decreased the fungal content in the *Penicillium*, *Aspergillus*, and *Paecilomyces variotii* group compared to continuous and intermittent use of night-time ventilation.

In the Grampos group, the mean concentration decreased by 5% and the standard deviation by 9% with the continuous ventilation compared to the pre-started ventilation. The intermittent ventilation decreased the mean content by 31% and the standard deviation by 35%, correspondingly. Thus, the pre-started ventilation increased slightly the bacteria content compared to continuous use of ventilation and considerably compared to the intermittent night ventilation. In the Gramneg group, the mean concentration decreased by 13% and the standard deviation by 20% with the continuous ventilation compared to the pre-started ventilation. The intermittent ventilation decreased the mean content by 32% and the standard deviation by 57% compared to pre-started ventilation. Thus, the Gramneg bacteria results followed rather closely the corresponding Grampos bacteria results.

The results reveal that the continuous and intermittent use of night ventilation reduced the average bacterial and total fungal concentration in indoor air in a long-term period. However, the systematic conclusions cannot be drawn between those strategies, because there was no statistically significant difference in the results of the collected six samples. Furthermore, similar measurements were carried out at different times of year that affected the result. In every case, the microbial content levels were rather typical. Usually, fungi are from outdoors or from a microbially damaged structure and bacteria are from humans. One probable reason for the slightly smaller level of concentrations of intermittent ventilation could also be that the indoor dust level can change during the measurement. In that sense, the more effective cleaning or lower activity in spaces may gradually decrease the amount of settled dust that can be seen in those box-plot patterns.

3.2. TVOC-Concentration

This chapter presents the results of the TVOC concentration. The results support the hypothesis of the effect of night ventilation methods on indoor air quality in the mornings and the effect of daily activities on TVOC concentration. The main concern was that stopping ventilation at night contributes to high levels of contaminants in the morning, and these compounds were sufficiently flushed out by ventilation before the occupied period. Correspondingly, the results are related to the hypothesis of indoor humidity level where the main concern was that stopping ventilation at night contributes to high levels of humidity in the morning because the humidity may accumulate and could not be flushed out before the occupied period.

3.2.1. TVOC in Weekday Mornings

Figure 6 shows TVOC concentration in an average weekday morning with the pre-started, continuous, and intermittent night ventilation methods. TVOC is measured using the metal oxide semiconductor method. Intermittent night ventilation provided the highest TVOC levels at night, but TVOC level decreased in the mornings to the same level as in the other test cases. The higher TVOC level was probably caused by the pressure differences between the different service areas because the operating times of air handling units were different during the intermittent test periods. This may cause ventilation imbalances transporting contaminants from one zone to another as an internal flow or as off-gassing from the interior materials. As it could be expected, TVOC levels were lowest at night by using the continuous ventilation. However, the TVOC level increased in the mornings in the same manner as in other night ventilation methods when the occupancy period began. Consequently, the results indicate that the night ventilation strategy is not relevant for the morning IAQ as long as the ventilation is started 2 h before space is used in normal conditions.

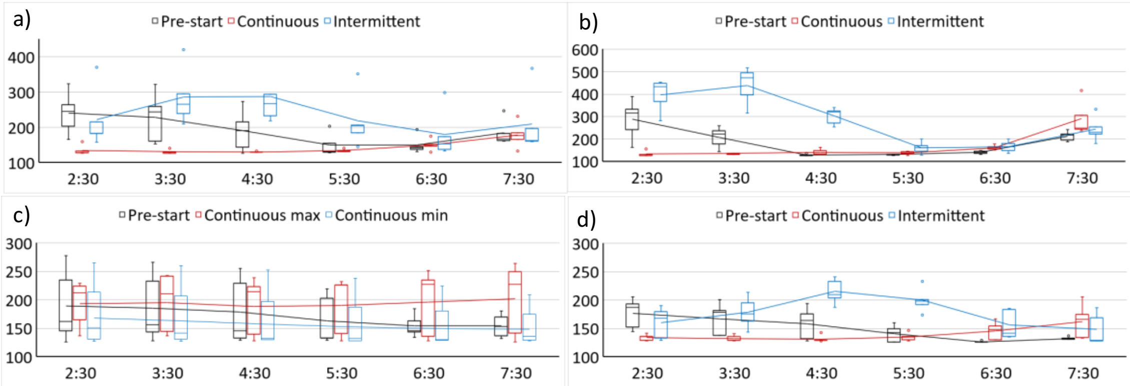

Figure 6. TVOC concentration [ppb] in the weekday mornings: (**a**) the classroom in primary school 1; (**b**) the playroom in kindergarten 1; (**c**) the classroom in secondary school (intermittent not available); and (**d**) the playroom in kindergarten 2. The line refers to average concentration. The vertical axis stands for concentration and the horizontal axis for early morning between 2:30 and 7:30.

3.2.2. TVOC, Night Ventilation, and Space Usage

Figure 7 on the left shows the temporal variation of TVOC concentration during the normal occupant periods with the monitored airflow rates, and pressure difference over the building external wall on the left panel. Figure 7 on the right shows the effects of space usage on TVOC-concentrations. The measurements were carried out during a weekday morning in the classroom in primary school 1 representing the general trend in these measurements. In building external wall, the measured pressure differences were mainly below 5 Pa in the measurements. This reveals that the supply and exhaust airflow rates were in balance.

The pre-started night ventilation method reduced the TVOC concentration to near the minimum level approximately two hours after the ventilation starts up. The continuous ventilation kept the TVOC concentration to a minimum at night. However, the TVOC concentration increased rather in a similar way in the morning than the pre-started ventilation method, although the TVOC level with the continuous night ventilation method was slightly lower at 7:00. The morning room cleaning was at 7:00–8:00 and the lessons began at 8:00–8:30. In intermittent ventilation, start-up, and shut-off the ventilation had a considerable effect on the TVOC concentration changes at night, such that the TVOC concentration decreased after the start-up and increased after the shut-off. This can be likely explained by material emissions or the different operation schedules of air handling units, allowing contaminants to spread between different indoor zones. This intermittent effect was observed in the other buildings as well. This means that the operation of the air-handling units in areas all operation modes must be adjusted and synchronized so that possible spread of pollutants does not occur.

The results indicate that the TVOC concentration level increased mainly due to daily space usage because the changes of TVOC-concentrations correlate well with the corresponding CO_2 concentration changes. This can be seen clearly in Figure 7 (right), where the CO_2 peaks are rather the same time than the local TVOC maximums. The CO_2 levels measured were at an acceptable level during the occupied hours (below 1000 ppm).

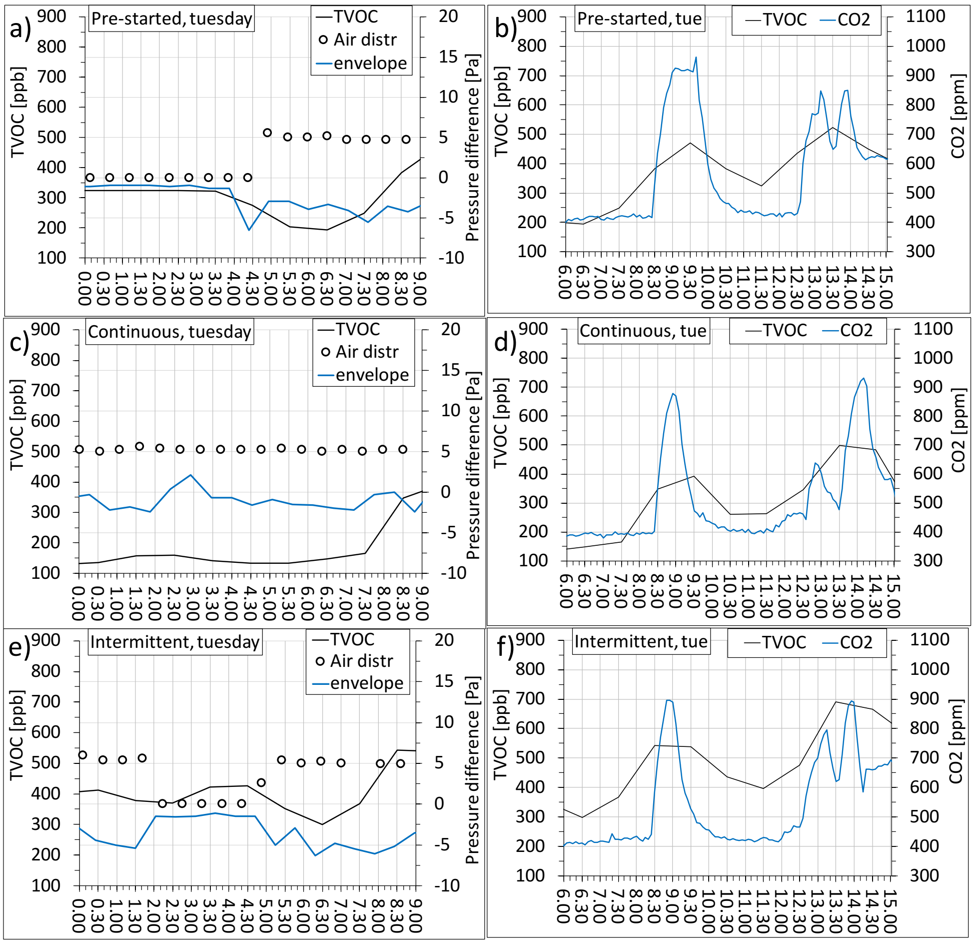

Figure 7. Indoor TVOC-concentration [ppb] related to the night ventilation [Pa], the pressure difference over the building envelope [Pa] on the left, and the CO_2 concentration [ppm] on the right. The primary school classroom in a weekday morning: (**a**,**b**) the pre-started ventilation; (**c**,**d**) the continuous use of ventilation; and (**e**,**f**) the intermittent use of ventilation.

3.2.3. TVOC and Thermal Conditions

Figure 8 shows the indoor and outdoor air temperature and relative humidity conditions regarding one classroom of the primary school 1. The results depict that in most of the cases, the indoor air temperature and humidity were quite stable at night, and started to increase at the beginning of occupied periods due to sensible heat gains and humidity load originating from pupils. This represents a general trend in measurements, indicating that the humidity was not accumulating at night although the ventilation was stopped. Additionally, the TVOC-concentration was changing with intermittent ventilation regardless whether the humidity level was stable. This, in turn, reveals that the indoor air temperature or the humidity were not affecting considerably on TVOC-variation.

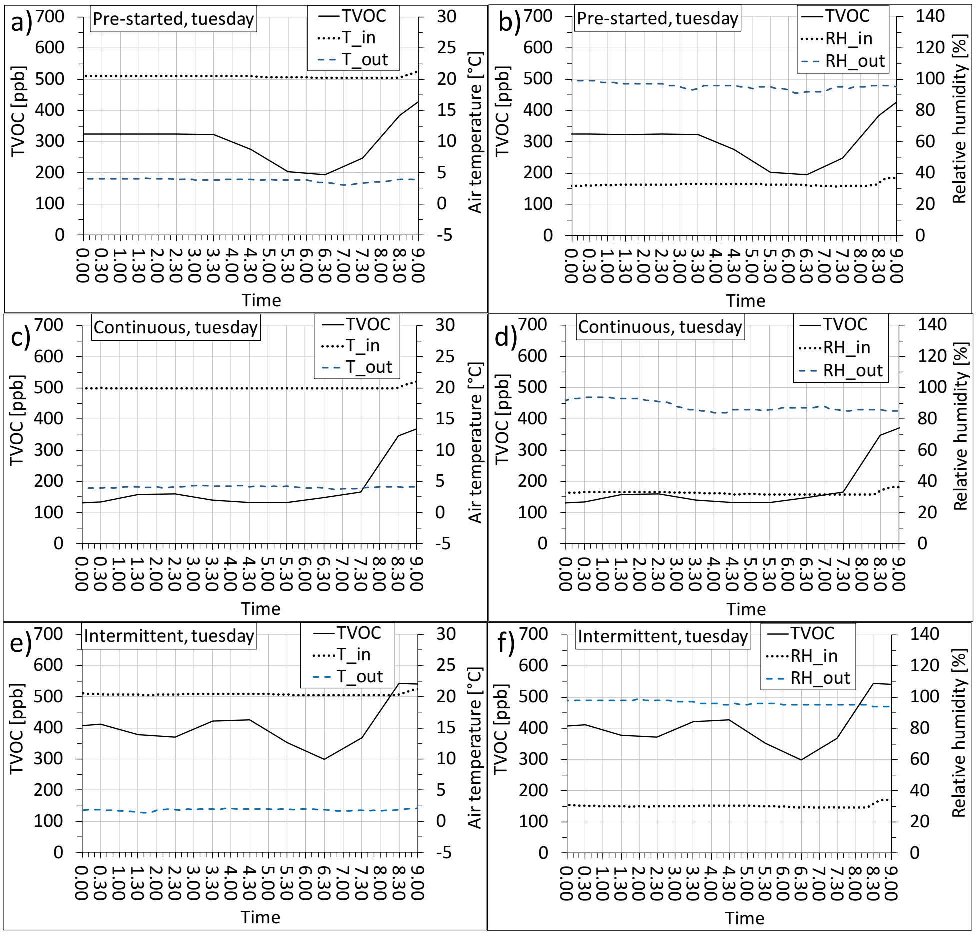

Figure 8. Indoor TVOC concentration related to air temperature and air humidity. The primary school classroom in a weekday morning: (**a**,**b**) the pre-started ventilation; (**c**,**d**) the continuous use of ventilation; and (**e**,**f**) the intermittent use of ventilation. T_in denotes the indoor air temperature, T_out refers to outdoor air temperature, RH_in is the relative humidity in indoor air, and RH_out is the relative humidity in outdoor air.

3.2.4. TVOC in Different Periods

Table 4 shows the averaged TVOC concentration during the week, the weekday at 8–16 and the morning at 6–8 with different night ventilation methods in selected spaces. Those results represent the general trend of measurements. The results show a reasonable variation of TVOC levels. The daily TVOC level was higher during the occupied hours than the morning period highlighting the effects of users' activities in those indoor environments. However, the intermittent ventilation provided higher TVOC concentration and deviation in a 1-week period than those other studied night ventilation methods. This difference was not so significant in the morning periods before occupancy (weekday at 6:00–8:00). It follows that the systematic and reliable differences between the night ventilation methods were not found and the average TVOC level varied case-dependently within the measurement uncertainty in these cases. However, the standard deviation was often smallest with the pre-started night ventilation method.

Table 4. Averaged TVOC concentration in different time periods.

TVOC	1 Week		Weekday 8–16		Weekday 6–8	
[ppb]	avg	sd	avg	sd	avg	sd
			classroom in primary school 1			
pre-started	238	85	330	96	167	31
continuous	210	87	325	23	165	26
intermittent	287	129	398	154	195	79
			playroom in kindergarten 1			
pre-started	223	75	222	14	177	12
continuous	191	95	341	40	226	42
intermittent	276	112	278	94	205	39
			playroom in kindergarten 2			
pre-started	186	62	263	15	130	2.1
continuous	180	87	317	70	154	23
intermittent	212	92	311	53	153	27
			classroom in secondary school			
pre-started	195	46	202	23	155	19
continuous max	194	79	272	88	199	61
continuous min	187	91	285	89	150	38

3.3. Particulate Matter in Ventilation Start-Up

This measurement was made to investigate the effects of ventilation start-up on the particulate matter concentration in indoor air. This is because the ventilation start-up will create a pressure surge that may throw particles from ductwork into indoor air. The particle measurement showed that when the fan started to operate, the particle concentrations approached rapidly zero in the connection duct just before the air terminal device. In the room, the PM10 concentration decreased from 20 to 10 µg/m^3 and PM2.5 from 6 to 3 µg/m^3 within 30 min (Figure 9). The concentration levels decreased on average 49% and 61%, respectively. Furthermore, the indoor particulate concentration was smaller than the outdoor concentration, indicating the indoor/outdoor rates of 0.3 and 0.2, respectively. The results suggest that the recommendation to start mechanical ventilation 2 h before the space usage is sufficient.

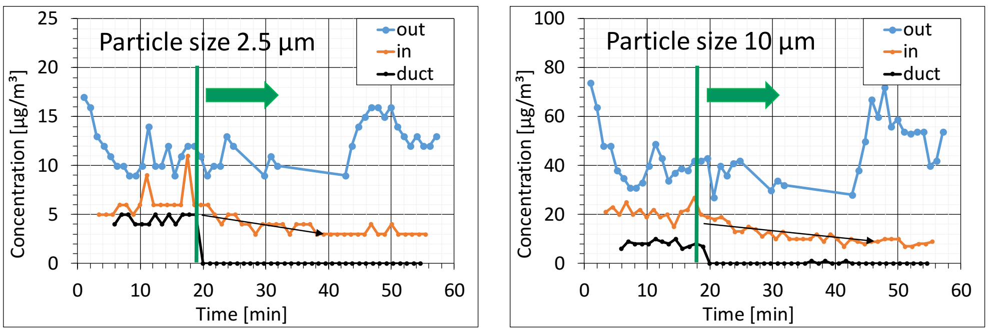

Figure 9. Measured particulate matter in first-floor group workspace when the ventilation started in the morning. The ventilation airflow rate was 2 L/s·m^2. The vertical line shows the start of mechanical ventilation. The black arrow shows a trend of decrease.

4. Discussion

The measurements were carried out in different seasons during the time period of 2019–2020. The buildings were selected from the different property owners to measure buildings that do not have the previously reported IAQ problems. In the measurement campaign, 5 buildings in autumn, 2 buildings in winter, 2 buildings in spring, and 2 buildings in summer season were measured. The field measurements lasted altogether 4–6 weeks in each building, and the choice of buildings had to be compromised in terms of cost and total time frame by measuring one or two buildings simultaneously. Consequently, the number of measured buildings was only 11, and therefore, the statistical representativeness was poor. The reliability of statistical evaluation can usually require 20–30 buildings in field measurements. Besides, the field measurements were made at different times of the year, which means that the buildings of the same type could not be directly compared with each other. In practice, the real challenge was to adjust exactly similar comparison cases, which is a rather well-known limitation in field experiments in non-controlled real indoor environments. However, the measuring instruments and analysis methods were of high quality, leading to reasonable observations in each building. As a result, new knowledge has been processed on indoor air quality and microbial concentrations in educational buildings.

The results indicate that a selection of the night-time ventilation method may have a smaller effect on the indoor air quality than that of a normal variation of those measured quantities. This was believed to have an association with indoor pollutant generation, interior usage, and season conditions. Consequently, the systematic similarities were not recognized with those night ventilation methods. The hypotheses were proposed on how indoor environments should be ventilated during unoccupied hours. The first hypothesis was related to what is the effect of night ventilation on morning indoor air quality. The results show that night ventilation is not necessary if the occupied ventilation is started 1–2 h before occupied periods. A 1–2-h flushing period should be also required after the space usage in the evenings. The common TVOC sources are personal, teaching, or cleaning products as well as interior building materials [39]. Furthermore, the cosmetics used by students may significantly increase TVOC levels [40]. Consequently, the daily space activities affect greatly the TVOC levels. The results showed that the daily TVOC level was higher than the morning level, highlighting the effects of activities in those indoor environments. Therefore, these results suggest concentrating on occupied ventilation time in improving wellbeing indoors. The existing pandemic has caused restrictions on space usage, which increased the demand for ventilation during the occupied hours. However, at night times, educational buildings are empty, and therefore night ventilation is useless in reducing the COVID-19 risk.

Another hypothesis was that the indoor humidity cannot be extracted if the ventilation is off. The indoor humidity level is generally determined by the outside air and the internal humidity and airflow. The key issue is the ventilation, and in these public buildings, the ventilation is 2–4 1/h, which means that the premises can be flushed well. The results indicate that night-time air temperature and humidity conditions were rather constant in the measured buildings, and as a consequence, the greatest effect on thermal conditions was usually the sensible heat gain and humidity load generated by occupants during the indoor environment activities. The results reveal that in the morning, all the studied night ventilation strategies proved a similar level of indoor air quality. The continuous ventilation maintained the TVOC concentrations at a low level during nighttime. However, if the ventilation system is operating continuously, the energy consumption can increase unnecessarily related to guarantee healthy and comfortable indoor climate conditions. Therefore, continuous ventilation is not necessary.

The ventilation efficiency is related to the air change efficiency [41]. This means that in night-time unoccupied conditions, the ventilation efficiency can be associated closely with the ventilation airflow rate, the supply air temperature, the room size, as well as the air distribution, and the pressure differences over the building envelope and between the spaces. In the spaces measured, the room heights were typical in education buildings (around 3 m), which means that the specific airflow rate described well the performance of the ventilation. In most cases, the air distribution was mixing ventilation from the corridor wall or the ceiling, and for example, displacement ventilation systems were not used in the buildings. The night purging efficiency will increase with the airflow rate. Additionally, the longer thrown patterns enhance mixing and diluting the pollutants more evenly over the total volume. However, the location of the extract is also important. Generally, a good result can be achieved if the short circuit between the supply and extract could be avoided. In larger room sizes, the number of supply and exhaust air terminal devices can be an essential matter. The spatial distribution of those devices may affect the local efficiency in the occupied zone because more devices can provide more uniform conditions by eliminating the differences and stagnant zones.

The small airflows are difficult to manage in practice. The Finnish building code suggests that minimum ventilation is 0.15 L/s·m^2 for unoccupied periods. This is difficult to adjust because usually in educational buildings, the minimum airflow of the air handling unit is on the order of 30% from the maximum one, and as a consequence, 0.15 L/s·m^2 can be much lower than that. Moreover, the small airflows may not be distributed in ductworks as designed, because those have been sized to greater ventilation airflows. In addition, the control devices are not able to control the small airflows, because the minimum speed of measuring devices is on the order of 1 m/s and the minimum airflow may provide the speed well below that. Besides, ventilation efficiency is poor with minimum airflow providing low throw lengths in mixing ventilation systems. However, the mixing in the occupied zone may be improved by using a non-isothermal cool supply air (e.g., 18 °C). That is proposed to be used with minimum ventilation. If the minimum ventilation is desired, there should be a separate system installed, but it seems rather unjustified according to this study. In this sense, the maximum intermittent ventilation can produce a slight advantage, although it may provide pressure differences while synchronizing different air handling units. The intermittent ventilation increased the night-time TVOC-concentrations at the highest level. This can be due to unbalance of supply and exhaust airflow rates. Generally, similar time schedules of air-handling units and exhaust fans are important. The airflow balances are recommended to be checked in the building commissioning phase and to ensure that the contaminants do not spread due to pressure differences between different zones. This means that the airflow measurements are suggested to be carried out in different control modes and paying special attention to the commissioning of VAV systems.

The settled dust samples indicate that the microbe levels were rather typical and the systematic conclusions cannot be drawn between the ventilation strategies during unoccupied periods, and there was no statistically significant difference between different ventilation strategies. Analyzed microbes were selected to describe large microbial groups rather than individual species. These qPCR assays are generally used to measure microbes in indoor air studies. Parallel results that were collected from one room were very similar. Blank samples and positive and negative controls in each step in the laboratory were also used. Problems with the Gram-positive bacterial assay from outdoor samples have been found earlier. The reason is unclear, but these problems can be due to inhibiting material e.g., organic material or pollen in outdoor samples. Problems were not seen in indoor samples. The results showed that intermittent ventilation provided a slightly lower level of microbial concentrations than those other methods. However, the reliable reason for that was not recognized in the analysis. One possible reason could be that the indoor dust level can change during the 6-week measurements, or the more effective cleaning or lower activity in spaces can gradually decrease the amount of settled dust in indoor environments during abnormal conditions for space users in the awareness of measuring instruments. The bacterial content is highly affected by the occupants and their indoor activities whereas the fungal content is affected more by the outdoor fungal content. Therefore, most probably, the night ventilation strategy did not have a considerable effect on those results.

Hypotheses about the use of night ventilation are useless when using effective pre-started morning ventilation. In schools and kindergartens, the energy use of ventilation can be the largest single factor, e.g., higher than the heat loss of the building envelope, and thus by optimizing the night use of ventilation, the building owners can keep energy consumption at a reasonable level. The energy consumption increases with ventilation operation time and airflow rates. It is energy efficient to use night ventilation only when necessary to ensure acceptable indoor air quality to individuals at the beginning of the space usage. However, healthy and comfortable indoor climate conditions should be guaranteed during the occupied hours because IAQ and thermal comfort are closely related to the wellbeing and performance of pupils and teachers in education buildings. Energy consumption can be reduced by operating night ventilation continuously with small airflow rates, but then the ventilation efficiency could be poor. Therefore, the pre-started ventilation with larger airflow rates could be a reasonable selection for night ventilation. This is supported by the knowledge that indoor air will typically change several times per hour.

The recommendations on further studies are associated with the performance of advanced air distribution methods as well as the night ventilation effectiveness in diluting and removing contaminants. CFD simulations can provide useful computational information about the probable trends of indoor airflow field under the measured boundary conditions and initial conditions. CFD simulations could be conducted by investigating air distribution scenarios with different pollutant sources and their spatial distribution. Artificial intelligence may be used in big data analysis.

5. Conclusions

In this study, the pre-started, continuous, and intermittent ventilation strategies were compared by assessing indoor air quality in field measurements. The motivation of the study was the knowledge cap on how different unoccupied ventilation strategies affect indoor air quality in the mornings and also during the occupied periods. Consequently, the main finding was that the daytime activities had the greatest effect on indoor air quality and the night-time ventilation had a negligible effect on TVOC and microbial concentrations if the ventilation is pre-started 2 h before the space use. Therefore, continuous ventilation is not necessary. The intermittent ventilation produced the highest TVOC concentrations at night was explained by the material emissions or the different operation times of air handling units in different service areas, allowing contaminants to spread between different zones. It follows that the synchronization of the operation schedules of air handling units can be challenging if intermittent ventilation is used. Overall, the selection of night-time ventilation method may have a smaller effect on indoor air quality than that of a normal variation of the measured quantities. This was believed to have an association with indoor pollutant generation, interior usage, and weather conditions.

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References

1. Seppanen, O.A.; Fisk, W.J.; Mendell, M.J. Association of ventilation rates and co2 concentrations with health andother responses in commercial and institutional buildings. *Indoor Air* **1999**, *9*, 226–252. [CrossRef] [PubMed]
2. Sundell, J.; Levin, H.; Nazaroff, W.W.; Cain, W.S.; Fisk, W.J.; Grimsrud, D.T.; Gyntelberg, F.; Li, Y.; Persily, A.K.; Pickering, A.C.; et al. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air* **2011**, *21*, 191–204. [CrossRef] [PubMed]
3. Wargocki, P.; Sundell, J.; Bischof, W.; Brundrett, G.; Fanger, P.O.; Gyntelberg, F.; Hanssen, S.O.; Harrison, P.; Pickering, A.; Seppanen, O.; et al. Ventilation and health in non-industrial indoor environments: Report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). *Indoor Air* **2002**, *12*, 113–128. [CrossRef]
4. Daisey, J.M.; Angell, W.J.; Apte, M.G. Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. *Indoor Air* **2003**, *13*, 53–64. [CrossRef] [PubMed]
5. Mendell, M.J.; Heath, G.A. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air* **2005**, *15*, 27–52. [CrossRef] [PubMed]
6. Chatzidiakou, L.; Mumovic, D.; Summerfield, A.J. What do we know about indoor air quality in school classrooms? A critical review of the literature. *Intell. Build. Int.* **2012**, *4*, 228–259. [CrossRef]
7. Haverinen-Shaughnessy, U.; Shaughnessy, R.J.; Cole, E.C.; Toyinbo, O.; Moschandreas, D.J. An assessment of indoor environmental quality in schools and its association with health and performance. *Build. Environ.* **2015**, *93*, 35–40. [CrossRef]
8. Wargocki, P.; Wyon, D.P. The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (rp-1257). *HVAC&R Res.* **2007**, *13*, 165–191.
9. Bakó-Biró, Z.; Clements-Croome, D.; Kochhar, N.; Awbi, H.; Williams, M. Ventilation rates in schools and pupils' performance. *Build. Environ.* **2012**, *48*, 215–223. [CrossRef]
10. CEN European Standard EN 15251:2007. In *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; European Committee for Standardization: Brussels, Belgium, 2007.
11. Montgomery, J.F.; Storey, S.; Bartlett, K. Comparison of the indoor air quality in an office operating with natural or mechanical ventilation using short-term intensive pollutant monitoring. *Indoor Built Environ.* **2015**, *24*, 777–787. [CrossRef]
12. Hunt, G.; Kaye, N. Pollutant flushing with natural displacement ventilation. *Build. Environ.* **2006**, *41*, 1190–1197. [CrossRef]
13. Coley, D.A.; Beisteiner, A. Carbon dioxide levels and ventilation rates in schools. *Int. J. Vent.* **2002**, *1*, 45–52. [CrossRef]
14. Griffiths, M.; Eftekhari, M. Control of CO2 in a naturally ventilated classroom. *Energy Build.* **2008**, *40*, 556–560. [CrossRef]
15. Almeida, S.M.; Canha, N.; Silva, A.; Freitas, M.D.C.; Pegas, P.; Alves, C.; Evtyugina, M.; Pio, C.A. Children exposure to atmospheric particles in indoor of Lisbon primary schools. *Atmos. Environ.* **2011**, *45*, 7594–7599. [CrossRef]
16. Chao, C.; Hu, J. Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving. *Build. Environ.* **2004**, *39*, 385–397. [CrossRef]
17. Artmann, N.; Manz, H.; Heiselberg, P. Climatic potential for passive cooling of buildings by night-time ventilation in Europe. *Appl. Energy* **2007**, *84*, 187–201. [CrossRef]
18. Lynch, P.; Hunt, G. The night purging of a two-storey atrium building. *Build. Environ.* **2011**, *46*, 144–155. [CrossRef]
19. Solgi, E.; Hamedani, Z.; Fernando, R.; Skates, H.; Orji, N.E. A literature review of night ventilation strategies in buildings. *Energy Build.* **2018**, *173*, 337–352. [CrossRef]
20. Le Dréau, J.; Heiselberg, P.; Jensen, R. Experimental investigation of convective heat transfer during night cooling with different ventilation systems and surface emissivities. *Energy Build.* **2013**, *61*, 308–317. [CrossRef]
21. Guo, R.; Heiselberg, P.; Hu, Y.; Johra, H.; Zhang, C.; Jensen, R.L.; Jønsson, K.T.; Peng, P. Experimental investigation of convective heat transfer for night cooling with diffuse ceiling ventilation. *Build. Environ.* **2021**, *193*, 107665. [CrossRef]
22. Santamouris, M.; Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **2013**, *57*, 74–94. [CrossRef]
23. Seppänen, O.; Brelih, N.; Goeders, G.; Litiu, A. Existing Buildings, Building Codes, Ventilation Standards and Ventilation in Europe. Final HEALTHVENT WP5 Report 2012. Available online: https://www.rehva.eu/fileadmin/EU_projects/HealthVent/HealthVent_WP5_-_Final_Report.pdf (accessed on 12 March 2021).
24. Carrer, P.; Fernandes, E.D.O.; Santos, H.; Hänninen, O.; Kephalopoulos, S.; Wargocki, P. On the development of health-based ventilation guidelines: Principles and framework. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1360. [CrossRef]
25. Sundell, J. On the history of indoor air quality and health. *Indoor Air* **2004**, *14*, 51–58. [CrossRef] [PubMed]
26. Herberger, S.; Herold, M.; Ulmer, H.; Burdack-Freitag, A.; Mayer, F. Detection of human effluents by a MOS gas sensor in correlation to VOC quantification by GC/MS. *Build. Environ.* **2010**, *45*, 2430–2439. [CrossRef]
27. Leidinger, M.; Sauerwald, T.; Conrad, T.; Reimringer, W.; Ventura, G.; Schütze, A. Selective Detection of Hazardous Indoor VOCs Using Metal Oxide Gas Sensors. *Procedia Eng.* **2014**, *87*, 1449–1452. [CrossRef]
28. Schütze, A.; Baur, T.; Leidinger, M.; Reimringer, W.; Jung, R.; Conrad, T.; Sauerwald, T. Highly Sensitive and Selective VOC Sensor Systems Based on Semiconductor Gas Sensors: How to? *Environment* **2017**, *4*, 20. [CrossRef]
29. WHO. *Health Effects of Particulate Matter: Policy Implications for Countries in Eastern Europe, Caucasus and Central Asia*; WHO Regional Office for Europe: Copenhagen, Denmark, 2013.

30. Diapouli, E.; Chaloulakou, A.; Koutrakis, P. Estimating the concentration of indoor particles of outdoor origin: A review. *J. Air Waste Manag. Assoc.* **2013**, *63*, 1113–1129. [CrossRef]
31. Myatt, T.A.; Johnston, S.L.; Zuo, Z.; Wand, M.; Kebadze, T.; Rudnick, S.; Milton, D.K. Detection of airborne rhinovirus and its relation to outdoor air supply in office environments. *Am. J. Respir. Crit. Care Med.* **2004**, *169*, 1187–1190. [CrossRef] [PubMed]
32. Frankel, M.; Timm, M.; Hansen, E.W.; Madsen, A.M. Comparison of sampling methods for the assessment of indoor microbial exposure. *Indoor Air* **2012**, *22*, 405–414. [CrossRef]
33. Adams, R.I.; Tian, Y.; Taylor, J.W.; Bruns, T.D.; Hyvärinen, A.; Täubel, M. Passive dust collectors for assessing airborne microbial material. *Microbiome* **2015**, *3*, 46. [CrossRef]
34. Leppänen, H.K.; Täubel, M.; Jayaprakash, B.; Vepsäläinen, A.; Pasanen, P.; Hyvärinen, A. Quantitative assessment of microbes from samples of indoor air and dust. *J. Expo. Sci. Environ. Epidemiol.* **2017**, *28*, 231–241. [CrossRef]
35. Haugland, R.; Vesper, S.U.S. Identification and Quantification of Specific Fungi and Bacteria. U.S. Patent Patent No. 6,387,652, 14 May 2002.
36. Haugland, R.A.; Varma, M.; Wymer, L.J.; Vesper, S.J. Quantitative PCR Analysis of Selected Aspergillus, Penicillium and Paecilomyces Species. *Syst. Appl. Microbiol.* **2004**, *27*, 198–210. [CrossRef] [PubMed]
37. Kärkkäinen, P.M.; Valkonen, M.; Hyvärinen, A.; Nevalainen, A.; Rintala, H. Determination of bacterial load in house dust using qPCR, chemical markers and culture. *J. Environ. Monit.* **2010**, *12*, 759–768. [CrossRef] [PubMed]
38. Haugland, R.A.; Siefring, S.C.; Wymer, L.J.; Brenner, K.P.; Dufour, A.P. Comparison of Enterococcus measurements in freshwater at two recreational beaches by quantitative polymerase chain reaction and membrane filter culture analysis. *Water Res.* **2005**, *39*, 559–568. [CrossRef] [PubMed]
39. Shendell, D.G.; Winer, A.M.; Stock, T.H.; Zhang, L.; Zhang, J.; Maberti, S.; Colome, S.D. Air concentrations of VOCs in portable and traditional classrooms: Results of a pilot study in Los Angeles County. *J. Expo. Sci. Environ. Epidemiol.* **2004**, *14*, 44–59. [CrossRef] [PubMed]
40. Leppänen, M.; Peräniemi, S.; Koponen, H.; Sippula, O.; Pasanen, P. The effect of the shoeless course on particle concentrations and dust composition in schools. *Sci. Total. Environ.* **2020**, *710*, 136272. [CrossRef]
41. Mundt, M.; Mathisen, H.M.; Moser, M.; Nielsen, P.V. *Ventilation Effectiveness: Rehva Guidebooks*; Federation of European Heating and Air-Conditioning Associations: Brussels, Belgium, 2004.