LOW CARBON LIVING CRC

Advanced hybrid ventilation systems for schools

Authors	Project Leader: Mattheos Santamouris Shamila Haddad, Riccardo Paolini
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1. EXECUTIVE SUMMARY

School buildings are considered an important building type in relation to the effects of indoor conditions on students' health, learning and performance [1]. In addition, teaching quality can be influenced by classroom conditions [2]. Indoor environmental conditions in schools are of particular importance, as children are less resistant to adverse environmental conditions compared with adults, and thus, the magnitude of the effects of poor indoor air quality and high indoor air temperatures on school work performance is suggested to be larger than that on office work performance by adults [3-5]. Field studies conducted in classrooms show that elevated temperatures may lead to reduced productivity [4]. The literature suggests that students' achievement is affected, because discomfort decreases the attention span when temperature and humidity exceed their comfort zone [6]. The most important variables that affect thermal comfort are air temperature, mean radiant temperature, relative air velocity, and humidity level as well as activity level and the thermal resistance of the clothing.

Further, rising respiratory disease has led to an increasing research focus on indoor air quality (IAQ) in schools. Children are more vulnerable to airborne pollutants than adults because their developing lungs breathe more air compared with their body sizes, and their underdeveloped ability to communicate concerns in response to pollutant levels. Ventilation is an effective strategy for controlling indoor air quality (IAQ) in school buildings. It supplies outdoor air, generally assumed to be clean, to reduce exposures to hazardous pollutants by removing the air pollutants from indoor environment. Consequently, it helps to reduce the associated risks for health, comfort and wellbeing, learning performance and productivity. Such risks are documented in the literature [7,8].

A review of 14 published studies in schools revealed that CO_2 in 30% of the investigated classrooms exceeded 1500 ppm [9]. The literature reported that low ventilation rates are common in schools and are linked to adverse health effects in both children and adults [10-11,1]. Moreover, increase in CO_2 concentrations by 1000 ppm is linked with an increase of absenteeism by 10–20% [12]. Increased outdoor air flow rate from to 12.8 l/s per person, combined with decrease of mean indoor CO_2 from 1050 to 780 ppm, led to a significant reduction of asthmatic symptoms in children from about 11% to 3.4% over a two-year period [13].

In addition, indoor air may contain contaminants that happen as airborne particles. The main indoor sources of particles in school environments include human activities, plants and building materials, especially mineral fibres [9]. Further, particles penetrate in the classrooms through ventilation and infiltration from the outdoor environment, particularly in urban areas affected by outdoor traffic and vehicle emissions. Students' sick building syndrome (SBS) symptoms and performance of schoolwork were also investigated as a function of the levels of indoor air pollutants and ventilation, and significant positive correlations were found between particulate matter (PM) and certain health symptoms [14].

Volatile Organic Compounds (VOCs) are chemical pollutants in the indoor air emitted from anthropogenic and biogenic sources namely solvents, paints, floor adhesives, cleaning products, furnishings, polishes and construction material [15-17]. VOCs in schools originate from a combination of emissions from indoor building materials, human activities and outdoor sources [9]. Research shows that in classrooms using chalk boards, the concentrations of particulate matter were high while classrooms using white boards marker had increased levels of VOCs [18].

Formaldehyde is an important chemical widely used by industry to manufacture building materials and numerous household products. Sources of formaldehyde include building materials, smoking, household products, and the use of unvented, fuel-burning appliances. Formaldehyde is a colourless, pungent smelling gas. It can cause watery eyes, burning sensations in the eyes and throat, nausea, and difficulty in breathing [19].

Poor indoor air quality and elevated air temperature is a common problem in most school classrooms worldwide. This problem is exacerbated when ventilation rates are too low to remove excessive heat, especially when teachers or school authorities keep windows closed to avoid discomfort caused by external noise and/or to prevent drafts. Furthermore, widespread and growing use of mechanical and electrical systems for achieving desired thermal conditions highlights the importance of investigating how design strategies for school buildings may help to achieve comfort conditions and ensure a healthy environment while also improving energy performance. It is argued here that examination of IAQ and thermal comfort for children could inform improved design of school buildings and thereby optimize conditions for students' performance and wellbeing. The main aim of this project is to develop and test a hybrid ventilation system to improve indoor air quality, achieve thermal comfort conditions, and at the same time reduce energy consumption and carbon emissions. It has been shown that the new ventilation system, and Healthbox, result in improved ventilation and air quality in the investigated school classroom. Further research is required to develop health-based ventilation guidelines for schools in Australia.

2. INTRODUCTION

There is much concern about indoor thermal comfort conditions in school buildings as research has demonstrated that it affects the health, learning and performance of students and staff. Moreover, thermal comfort conditions in schools are of particular importance, as children spend almost one third of their day inside classrooms. Also, children are less resistant to adverse environmental conditions compared with adults.

Overheating of urban areas caused by the combined effects of global climate change and the urban heat island phenomenon is leading to increased thermal discomfort in schools. The widespread and growing use of air conditioning systems as a solution to maintain a comfortable indoor environment results in increased energy consumption for cooling and carbon emissions and exacerbates the energy bills of schools. Providing good indoor thermal comfort conditions in school buildings that enhance the wellbeing and learning performance of students while maintaining a low energy consumption and carbon footprint is an obvious necessity.

In this context, this project investigates hybrid solutions using enhanced ventilation in order to achieve indoor comfort conditions and at the same time reduce energy consumption and carbon emissions and then test it in the selected school building located in Sydney, which co-funded this project. In order to achieve this objective, the following activities have been carried out:

- Assessment of the thermal comfort conditions and air quality over 1 year (2018-2019)
- Investigation of passive/ hybrid solutions for improving thermal comfort conditions of school classrooms
- Installation and evaluation of a hybrid ventilation system to improve thermal comfort and air quality

The main outcome of the project helps to develop design solutions for enhanced thermal comfort and low carbon footprint in school buildings. This new knowledge and the proposed design solutions is beneficial for other school buildings.

This report is presented in five main chapters.

- Methodology of the study (Chapter 3)
- Indoor air and environmental quality measurement (Chapter 4)

  a) longitudinal monitoring of air quality and thermal environmental parameters

  b) Simultaneous objective and subjective experimental campaign to assess indoor thermal comfort and air quality (before and after installation of the ventilation system) was conducted from 21/08/2018 to 03/09/2018 (cold season) and from 08/04/2019 to 12/04/2019 (mid-season).
- VOCs measurement (Chapter 5)

  Investigation of hybrid ventilation for improving indoor environmental quality. Detailed VOCs measurements and analysis after installation of the new ventilation system 13/05/2019 and 14/05/2019. Classroom with ventilation is compared with classroom without ventilation system.
- Infiltration and ventilation rate measurement (Chapter 6)

  Assessment of ventilation and infiltration condition before installation of the new system – tracer gas measurement was performed on 11/10/2018.
- Introduction to technical properties of the ventilation system and HEALTHBOX 3.0 (Chapter 7)

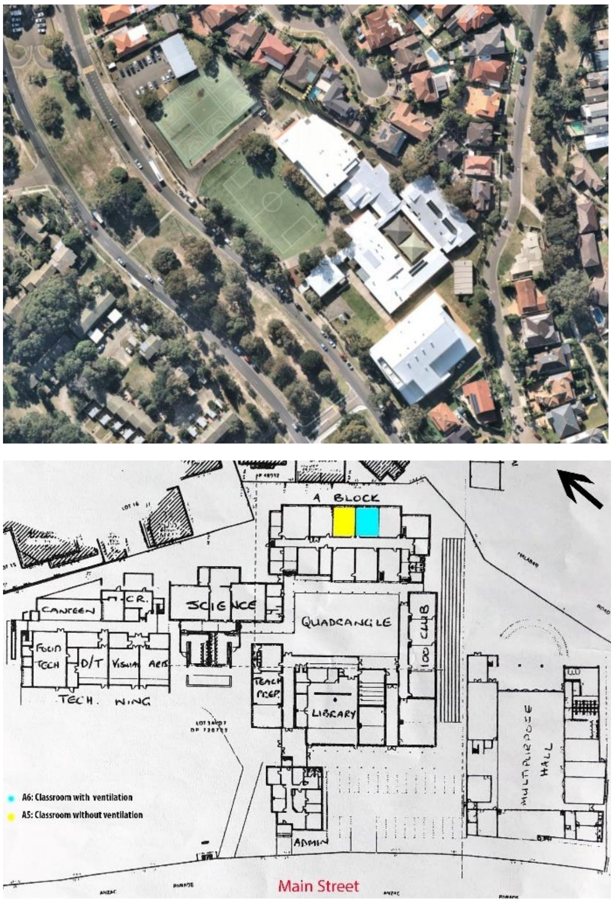
  Installation of the hybrid ventilation system was finalised on 22/01/2019. However, it was under maintenance until mid-February 2019. Technical details of the ventilation systems installed in the classroom in provided in Chapter 4.

3. METHODOLOGY

Participating school

This study was performed in St. Spyridon College located in Maroubra, Sydney. The participating school building was equipped with split systems as the main source for heating and cooling. Two adjacent classrooms shown in Figure 1 were selected to perform a longitudinal study to investigate indoor air and environmental quality of the classrooms.

Figure 1. map and location of the school and surveyed classrooms



St. Spyridon College

Data collection protocol

The main objective of the monitoring campaign was to obtain data (temperature, humidity, CO_2, and air quality) in the school classroom. The monitoring campaign was performed to assess the existing situation in terms of indoor environmental quality, investigate potential health impacts, understand the interventions needed to achieve acceptable indoor environmental conditions to avoid negative impacts on health. The experimental monitoring campaign was carried out continuously from April 2018 to May 2019.

To examine the thermal perception of children in the classrooms, two fieldwork campaigns were conducted in during cool and warm conditions of the local school year (2018-2019). Each campaign of the field study included subjective and objective approaches: 1) classroom environmental measurements and personal variable estimation and 2) thermal comfort field surveys.

Fieldwork combined simultaneous measurement of physical variables of the classrooms with survey of students' subjective responses conducted on 'right here, right now' basis, which records subjects' perceptions of the immediate thermal environment at the time the subjective survey was administered, students' general health and behavioural adaptation to classroom thermal environment. The teachers distributed the questionnaire in each classroom at the survey time. During the survey, all subjects were asked to perform as they do routinely to stay comfortable in the classroom. Questionnaires were specifically designed for the target age group based on developmental psychology [20]. Given the concern with the quality and reliability of subjective responses, it is necessary to confirm techniques for designing an effective questionnaire for evaluating children's perception of thermal comfort in the classroom. Figure 2 and Figure 3 show examples of illustrations designed for surveying children [20]. A sample of questionnaire is provided in Appendix 1.

Figure 2. Seven-point thermal sensation scale

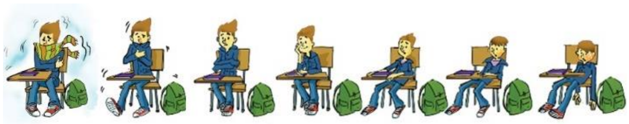


Figure 3. Three-point scale representing levels of tiredness

Experimental campaign and specification of the instrument

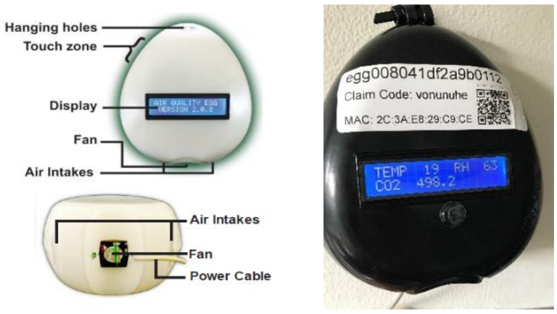
The indoor Air Temperature (T_a), Relative Humidity (RH), and Carbon Dioxide (CO_2) were monitored in this study from April 2018 to May 2019. Measurements were conducted by sensors placed in appropriate locations inside the classrooms. The sensors were left in that position for the duration of the monitoring period. The logger was positioned away from heat emitting sources, direct sunlight, or excessive moisture exposure.

Indoor Air Quality Egg recorder

Two air quality Egg sensors (Figure 4) produced by Wicked Device (Ithaca, New York) were used in this study. The Air Quality Egg version 2 Model D is a Wi-Fi enabled sensor unit which detects temperature, relative humidity, and carbon dioxide (CO_2). It displays readings on the front panel and uploads them to the internet via Wi-Fi network. The air quality Egg sensor recorded data every 1-min and was placed in a well-ventilated and excessive heat and moisture protected position of the classroom. Data was recorded by the sensor and

monitored regularly. The sensor enables real-time monitoring and notified through mobile application when there was a network problem. Measurements were recorded with an interval of one minute, and then averaged over 30 minutes for analysis. The accuracy of temperature and relative humidity are ±0.2°C and 1.8% over typical ranges, respectively. The measurement range of the temperature and humidity sensors is 0 to 50 °C and 0 – 95% (humidity accuracy below 10% and above 90% no worse than 4% RH). The accuracy of CO_2 sensor is 0-10,000 ppm (accuracy: ± 30 ppm ± 3 % of measured value within specifications, sensitivity: ± 20 ppm ± 1 % of measured value within specifications).

Figure 4. Indoor Air Quality Egg



LOGTAG temperature recorder

To monitor outdoor temperature during the experiment, one Logtag® TRIX-16 temperature recorders (Figure 5) was installed in UNSW Clovelly campus which is 4 km away from the participating school. The Logtag TRIX-16 temperature recorder features high resolution temperature readings over a measurement range of -40°C to +85°C, with the resolution of 0.1°C and the accuracy of ±0.5°C for temperature between -20°C and +40°C and ±0.7°C for temperature range of +40°C to +60°C. The recording interval was half hourly in this study. LogTag® Analyzer software and reader were used to archive the data and export them to other programs for the purpose of analysis.

Figure 5. Logtag® TRIX-16 temperature recorder

Series 500 – Portable Air Quality Monitor

The Series 500 air quality sensor enables accurate real-time surveying of common outdoor air pollutants, in a portable handheld monitor (Figure 6). Interchangeable sensor heads enable measurement from a choice of different gases or particulates. For particles, the accuracy of factory calibration is ± (0.002 mg/m^3 + 15 % of reading) and resolution is 0.001 mg/m3. For formaldehyde, he accuracy of factory calibration is <±0.05 ppm 0-0.5 ppm, and <±10% 0.5-10ppm. The resolution is 0.01ppm. The TVOC sensor has an accuracy of <±0.1 ppm + 10% and resolution of 0.1ppm. The Aeroqual Air Quality Monitor was used to measure PM10 and PM2.5 simultaneously, Formaldehyde, and TVOC.

Figure 6. The Aeroqual Air Quality Monitor

LSI Heat Shield

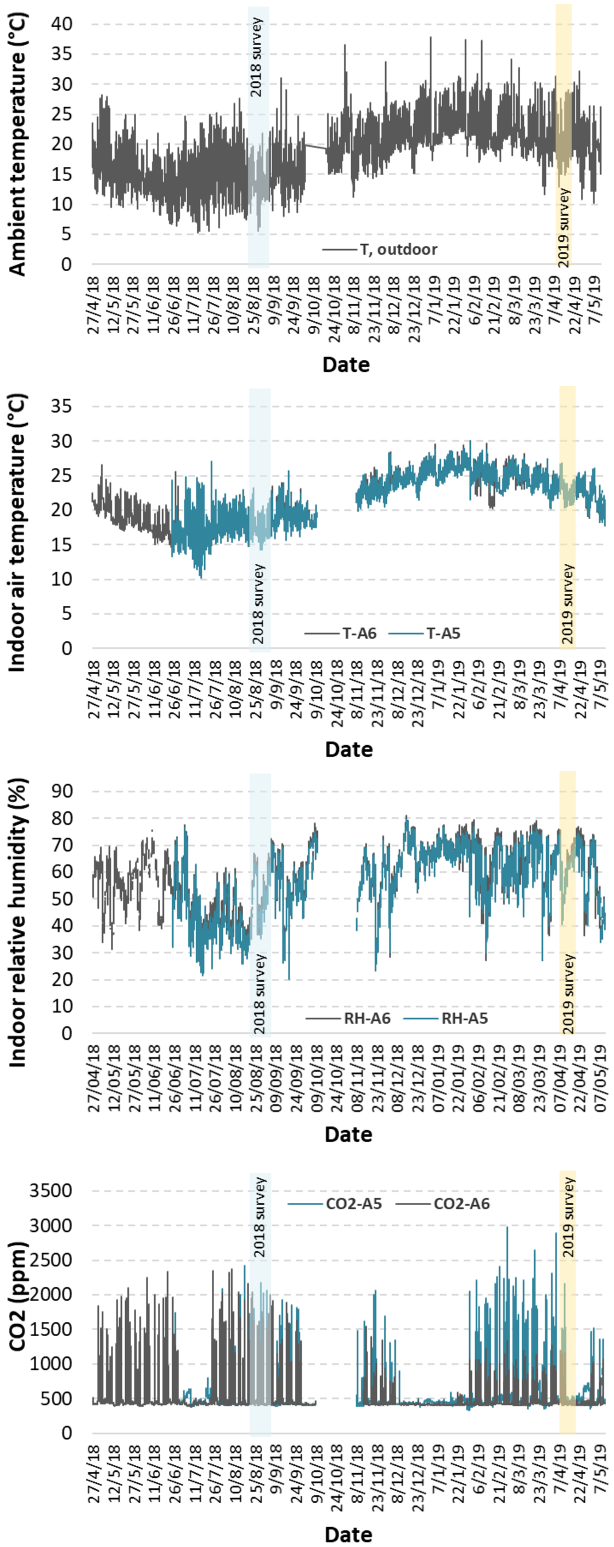
Heat Shield is equipped with built-in sensors to measure globe temperature (tg), wet bulb temperature (tnw), dry bulb temperature (ta) and relative humidity (rh). All sensors are designed in compliance with ISO7726. Heat Shield supports a 5 cm (2”) black globes thermometers and an external anemometer for air speed (va) measurement. LSI Heat Shield was only used during the survey period. It was located near the centre within the vicinity of the students’ desks away from heat-emitting educational electronic devices (e.g., laptop, monitor) to avoid any interference in the readings. Care was also taken to minimize the risk of instruments being accidentally bumped. The accuracy of globe and dry bulb thermometer is ± 0.3°C, and ± 0.8°C ±0.4 °C (10-40°C), respectively. The accuracy of relative humidity is 1.8 %RH (10-90%) and hot wire anemometer is accurate within the specification of ±10 cm/s (0.5÷1.5 m/s) 4% (>1.5 m/s).

Figure 7. LSI Heat Shield

4. INDOOR ENVIRONMENTAL AND AIR QUALITY MEASUREMENT

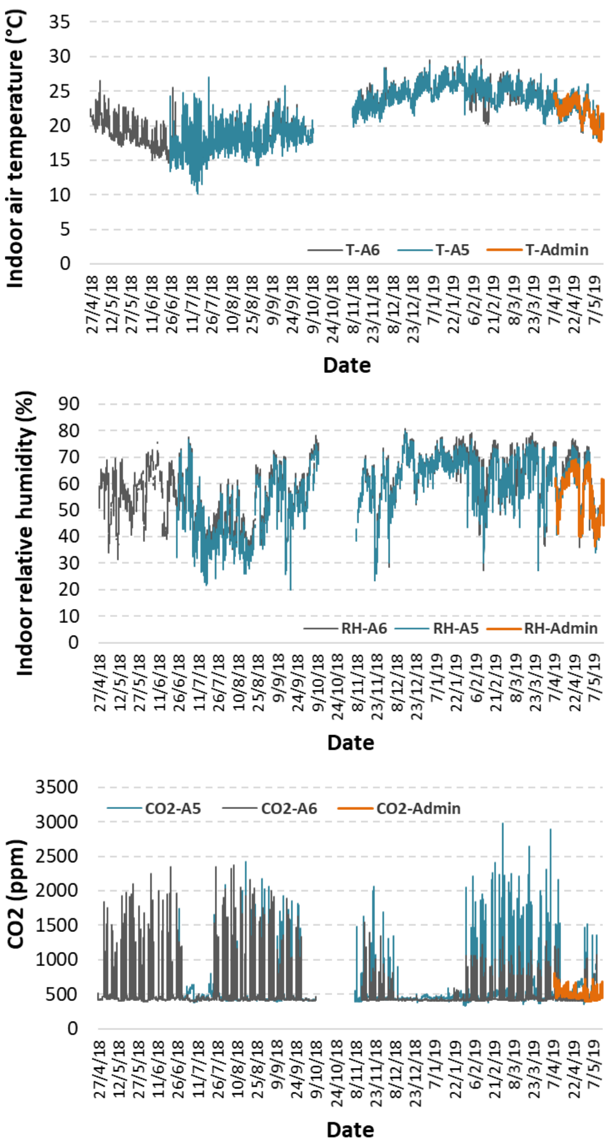
Figure 8 shows the results of monitoring during cold and mi-season namely outdoor temperature, indoor air temperature, indoor relative humidity, and CO_2.

Figure 8. Results of monitoring during cold and mid-season



During the monitoring period indoor temperature varied between 10.2°C and 30.0°C, while outdoor temperature ranged from 18.5°C to 37.9°C from April 2018 to May 2019. Relative humidity spaned from 20.1% to 80.9%. During the measurement period half hourly CO_2 in the classrooms reached 2981 ppm. However, CO_2 exceeded 3100 ppm when one-minute data was used. Outside survey campaign, heating and cooling systems were used occasionally which made slight differences in temperature and humidity of the investigated classrooms. During winter period windows were often closed due to the weather which cause CO_2 exceeding the recommended thresholds. ASHRAE 62.1 [21] recommends a threshold of 1000ppm for occupant comfort, and NCC IAQ Verification Method suggests 850 ppm. The background level of CO_2 concentration in air is below 400 ppm [22]. Results of measurements in school administration office is given in Figure 9. Office is normally occupied by three to four staffs and located near the main gate.

Figure 9. Results of monitoring including measurements in admin office.



As depicted, after installation of the ventilation system, during mid-season 2019, CO_2 was still high in A5 (classroom without ventilation), while it significantly reduced in A6 (classroom with hybrid ventilation). Information about ventilation system is provided Chapter 6.

Figure 10 compares CO_2 concentration in classrooms with (A6) and without ventilation system (A5). It is shown that air quality is significantly improved after installation of the ventilation. During winter school hour (Figure 11), both classrooms show similar rate of CO_2 level, while the maximum CO_2 concentration was slightly higher in A6. It should be noted that boxplots in Figure 10 and Figure 11 included data obtained during school holiday or hours that classrooms were not occupied.

Further, sample t-test was performed which indicates the difference between the mean value of CO_2 concentration in the classroom with ventilation system (A6) and the classroom with no means of ventilation (A5) is statistically significant ($p<0.001$).

Figure 10. Box plot of CO_2 after installation of ventilation system-midseason 2019

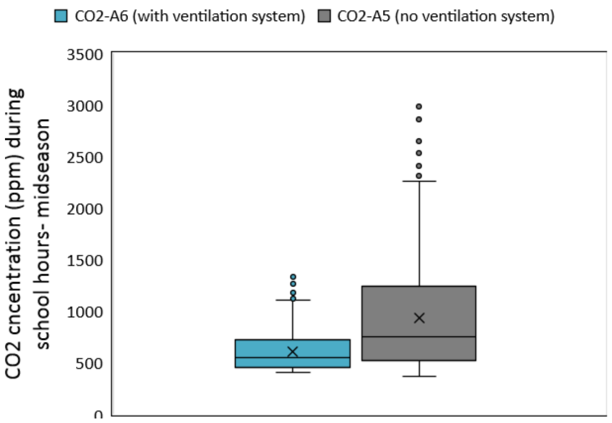
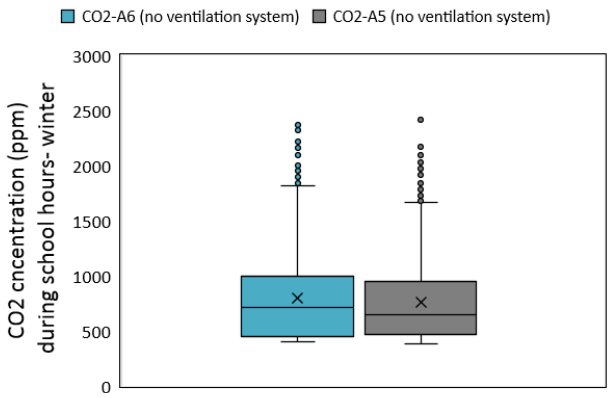


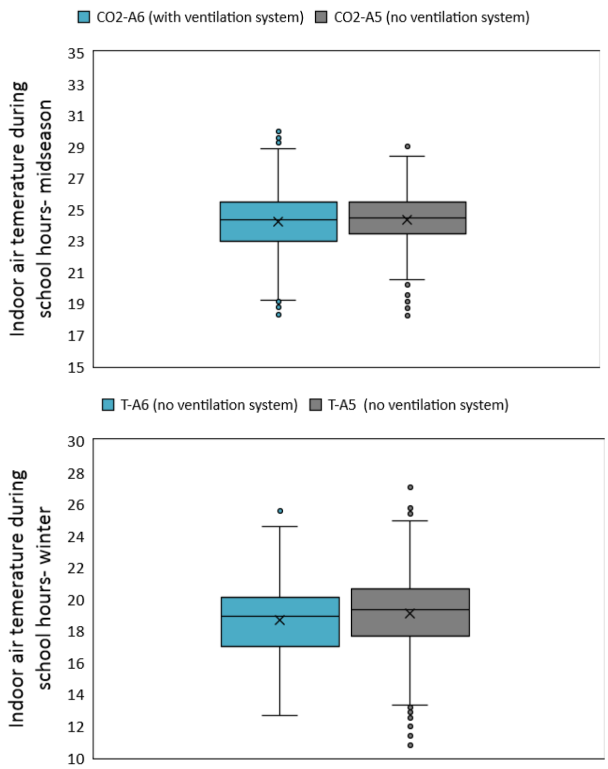
Figure 11. Box plot of CO_2 before installation of ventilation system-winter 2018



Elevated CO_2 levels indoors can cause health problems, e.g. headaches and fatigue, and may cause changes in respiratory patterns. Increasing concentrations will lead to dizziness, confusion, dyspnoea, sweating, dim vision followed by vomiting, disorientation, hypertension, and ultimately loss of consciousness [22]. Given both the importance of air quality to human health in general and the considerable time students spend in the school classrooms, it is important to improve indoor air quality (IAQ) in schools.

When indoor air temperature of the two investigated classrooms were compared both classrooms present similar indoor air temperature being slightly warmer in A5 (Figure 12).

Figure 12. Box plot of Indoor air temperature (°C) during school hours (mid-season 2019 (top), winter 2018 (bottom)



Volatile Organic Compounds (VOCs)

To understand the effects of ventilation system installed in classroom A6 (see Chapter 6), this study performed extensive analysis of Volatile Organic Compounds (VOCs). Results of VOCs measurement and analysis are presented in Chapter 4.

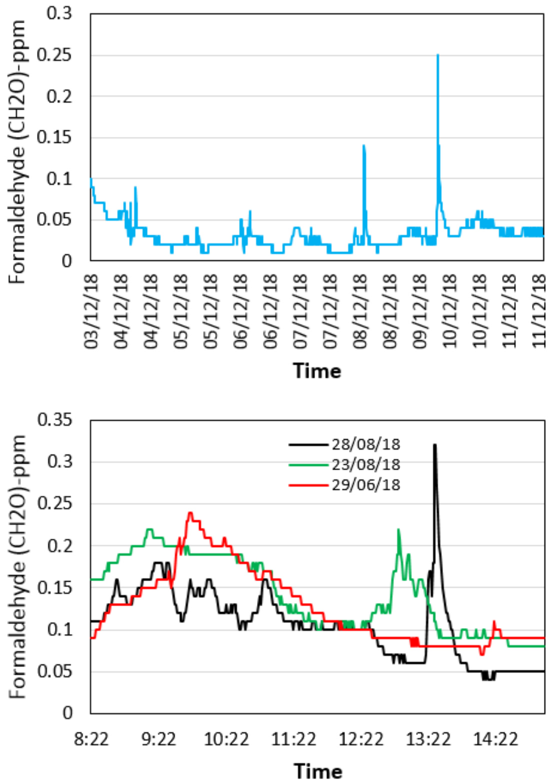
Formaldehyde (CH2O)

Formaldehyde is one of the major health issues concerning indoor chemicals. Manufactured goods that hold formaldehyde can release formaldehyde gas into the atmosphere namely, school building construction and materials.

In this study, Formaldehyde was measured in the classroom (A6) during different periods of the school year: a) over an extend period of one week in December 2018

(including weekend and unoccupied condition), b) over 8 hours in three normal school days.

Figure 13. Formaldehyde (CH2O) level in the classroom over 8days (top) and over one day (bottom)

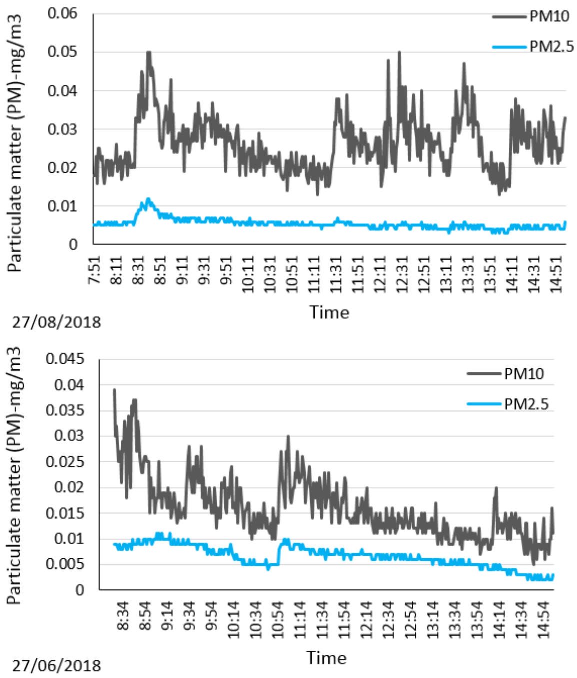


The 8-hours average Formaldehyde varied between 0.1 ppm to 0.14 ppm (Figure 13) which fell below the recommended limits.

Particulate matter (PM)

Indoor level of PM in classrooms is the outcome of both outside and indoor sources. Particulate matter (PM) was measured during school day (about 8 hours) for two different days. Results are presented in Figure 14. During the first day, PM10 varied between 5 to 39 μm/m^3 (8-hour mean: 16±6 μm/m^3) and PM2.5 was within a range of 2 to11 μm/m^3 (8-hour mean:7±2 μm/m^3). In the second day, PM10 ranged from 1 to 50 μm/m^3 (mean: 26±7 μm/m^3) and PM2.5 was within a range of 3 to 12 μm/m^3 (mean:6±1 μm/m^3). The levels of particles were below the recommended limits, and this is more likely explained by the low traffic and distance from the road.

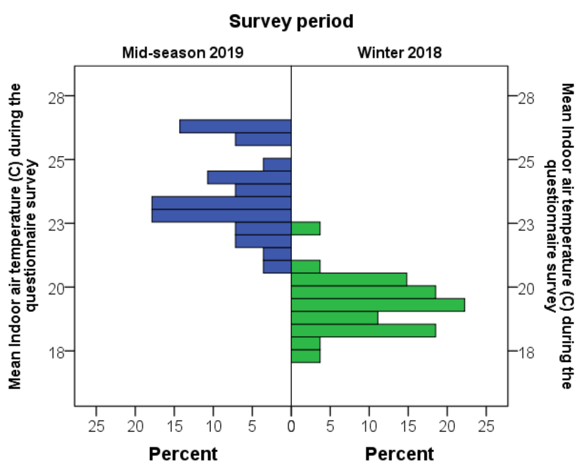
Figure 14. PM 10 and PM 2.5 during 2 school day



Indoor thermal environment and air quality during the questionnaire surveys

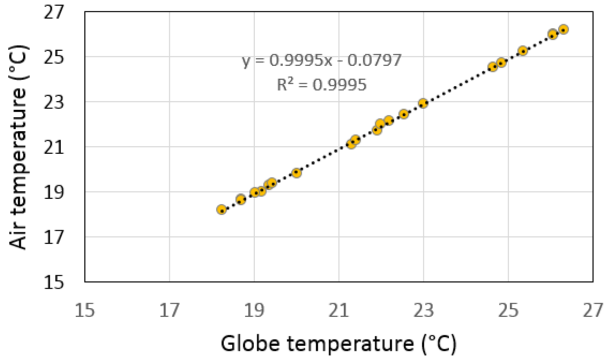
Indoor air temperature varied between 20.7 and 26.4 °C with the mean value of 23.7 °C during mid-season 2019 questionnaire survey. During winter questionnaire survey, the average indoor temperature was 19.3 °C (Figure 15). Indoor temperature fell within a range of 17.3 and 22.4 °C since no heating system was used in the classrooms.

Figure 15. Frequency of indoor air temperature during survey period



LSI thermal shield was used in one of the classrooms to measure other thermal variables namely globe temperature and wind speed. Wind speed were mostly below 0.1 m/s which is typical of a classroom. Figure 16 shows the relationship between globe temperature and indoor air temperature during the measurement. The globe temperature is commonly used to estimate the mean radiant temperature [23].

Figure 16. relationship between indoor air temperature and globe temperature



The average CO_2 concentration during winter survey period was higher than that during mi-season 2019 survey period. CO_2 was ranging between 442 ppm and 1510 ppm during mid-season and from 718 ppm to 2114 ppm during winter survey period. The mean CO_2 level in classroom A5 and A6 were similar during mid-season survey being 792 ppm and 690 ppm, respectively. During winter period, mean CO_2 level was 1327 ppm and 1465 ppm in A5 and A6, respectively (Table 1).

Table 1. Statistical summary of CO_2 level during survey periods

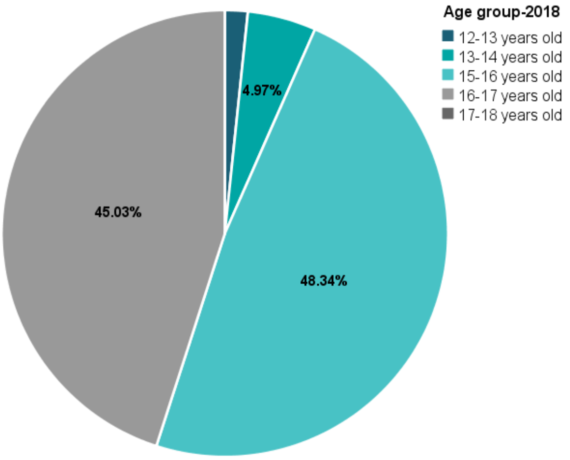
Survey period				Statistic
Mean CO2 (ppm) during the questionnaire survey	**Mid-season**	Mean		744.5
		95% Confidence	Lower Bound	639.1
			Upper Bound	849.8
		Median		647.2
		Std. Deviation		271.7
		Minimum		442.3
		Maximum		1510.6
		Range		1068.3
		Interquartile Range		406.0
	Winter	Mean		1393.9
		95% Confidence	Lower Bound	1226.4
			Upper Bound	1561.5
		Median		1293.1
		Std. Deviation		423.4
		Minimum		718.9
		Maximum		2114.6
		Range		1395.7
		Interquartile Range		705.9

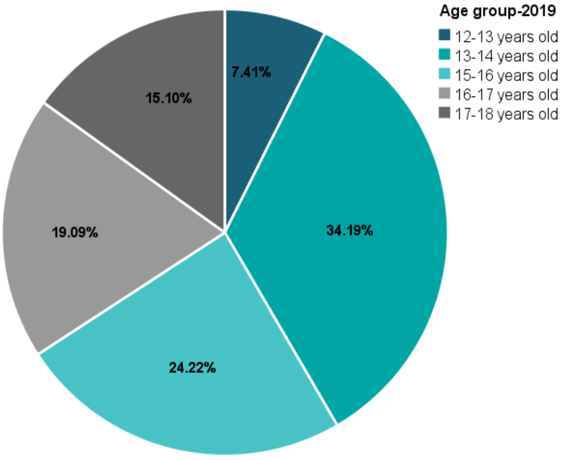
Assessment of the subjective votes

Before analysis subjective data were checked. Inconsistent, incomplete, and responses from sick subjects were excluded from the spreadsheets. People voting (-2, -3) or (+2, +3) on the seven-point thermal sensation scale are uncomfortably cold or warm, respectively; by logical extension, this means they should not want to enhance that feeling of being too cool or warm, making the conditions even more uncomfortable. A post-processing of all the administered questionnaires shows that only small number of students provided inconsistent votes, which were excluded from the dataset before analysis. This refers to the votes of the students at extreme thermal sensation (±2, ±3), with simultaneous preference for the cooler or warmer environment. In total, 376 (28 class-survey) and 306 questionnaires (27 class-survey) were pooled during winter and summer, respectively.

Figure 17 shows distribution of the participants age group during winter (top) and mid-season survey (bottom). A higher percentage of students participating in this study were 13-16 and 15-17 years old during mid-season and winter survives, respectively.

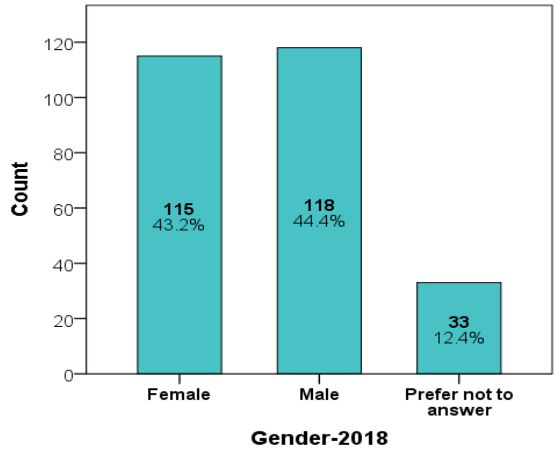
Figure 17. Distribution of the participants age group during winter (top) and mid-season survey (bottom)

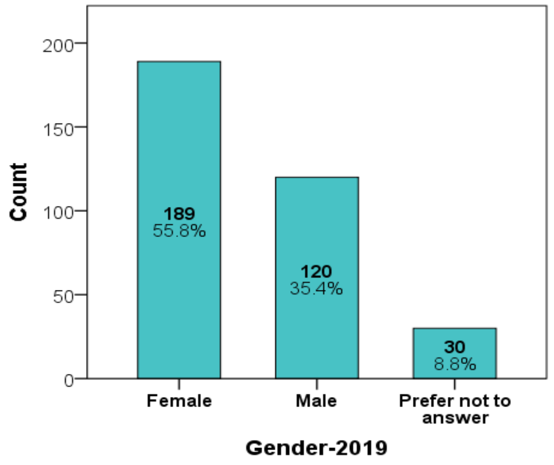




During winter period, the percentage of female and male students were similar (Figure 18), while during mid-season a higher percentage of participants were females (56%).

Figure 18. percentage of girls and boys during winter (top) and mid-season survey (bottom)

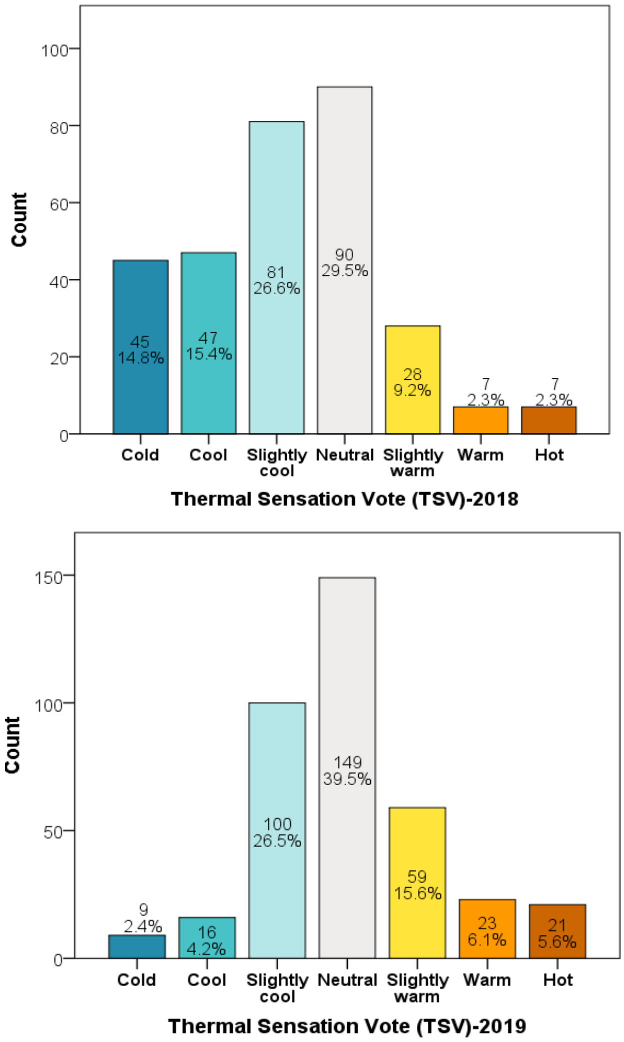




The environmental conditions were measured by researchers while simultaneously the thermal responses of the subjects were recorded by asking their comfort votes on the original seven-point psycho-physical ASHRAE thermal sensation scale [24] ranging from cold (-3) to hot (+3), with neutral (0) in the middle. Time and temperature were recorded for further analysis to derive comfort temperature of students.

We used ASHRAE thermal comfort scale to understand thermal sensation of students. As shown in Figure 19, 30.2% of students feel uncomfortably cold during winter, 26.6% feel slightly cool and 29.5% feel neutral (neither cool nor warm). During mid-season survey 2019, over 81% of students feel neutral by voting on the three-central categories of the comfort scale. 11.7% of students felt uncomfortably hot which was higher than the percentage of students feeling uncomfortably cold during the mead-season.

Figure 19. Occupants perception of thermal comfort during winter (top) and summer (bottom)



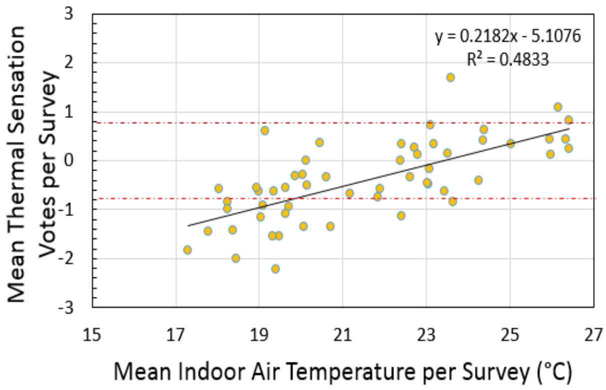
Based on the results of the right-here-right-now thermal sensation survey during summer 2019 (described above), we derived the acceptable range of temperature for occupants. The acceptable range is the comfort temperature band within which the great majority of people are comfortable. The mean thermal sensation of occupants in relation to the indoor air temperature of the dwelling is used to derive comfort zone limits for 80% satisfaction. As defined in ASHRAE 55 [24], comfort zone refers to conditions falling within a range from -0.5 to +0.5 in which predicted percentage of dissatisfied people is expected to be 20%. The 20% rate of dissatisfaction corresponds to 10% dissatisfaction for general thermal discomfort, when -0.5 < predicted mean vote of occupants < 0.5, and an additional 10% dissatisfaction due to local discomfort [24]; i.e. discomfort perceived in particular parts of the body caused by radiant temperature asymmetry, draft, vertical air temperature difference between the ankle and the head level, and floor surface temperature. The overall rate of dissatisfaction (20%) is related to the limits of ±0.85, which assumes 80% of votes falling inside the central three categories of the ASHRAE scale.

To find the empirical limits of acceptable thermal environments for 80% satisfaction [18], in line with this method, the indoor temperature was calculated for the mean thermal sensation votes (TSV) of ±0.85 using the linear regression model.

In this study, the neutral temperature for the sampled students during the survey period was derived for the whole survey period (combined winter and mid-season) using mean thermal sensation votes of students and air temperature per survey.

As shown in Figure 20, neutral temperature for students is derived to be 23.4 °C. Working on the industry-accepted assumption that an acceptable range of indoor operative temperatures corresponds to group mean thermal sensations of −0.85 through to +0.85, this research found that participated school children felt comfortable within an indoor temperature range of 19.5 °C to 27 °C. Despite the lower-than-expected neutrality derived for school children, participated school children demonstrated considerable adaptability to indoor temperature variations, with one thermal sensation unit equating to approximately 4.6°C indoor air temperature.

Figure 20. Linear regression analysis of thermal sensation against classroom temperature



As shown in Figure 21, during winter survey a larger percentage of students wanted to feel warmer (57%) than those who preferred a cooler or no change in the classroom. During mi-season, the percentage of ‘No change’ votes (42%) was higher followed by the percentage of students wanted to be ‘Cooler’ (37%).

Figure 21. Thermal preference votes during winter (top) and mid-season (bottom)

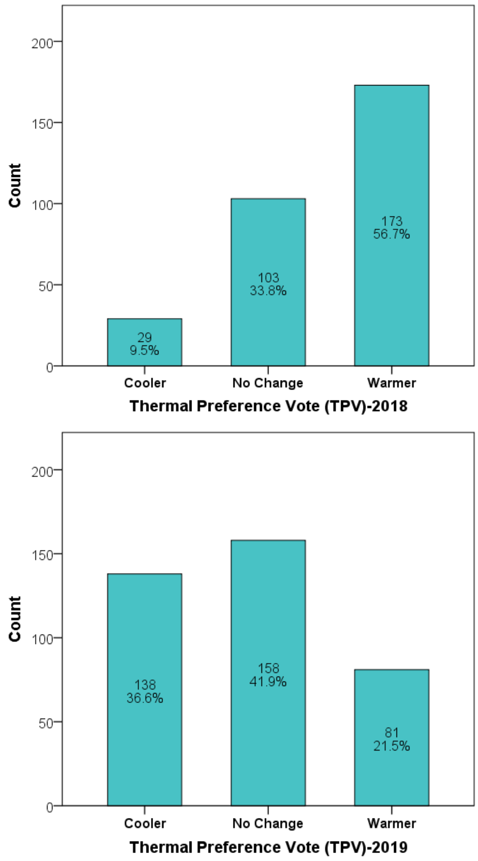
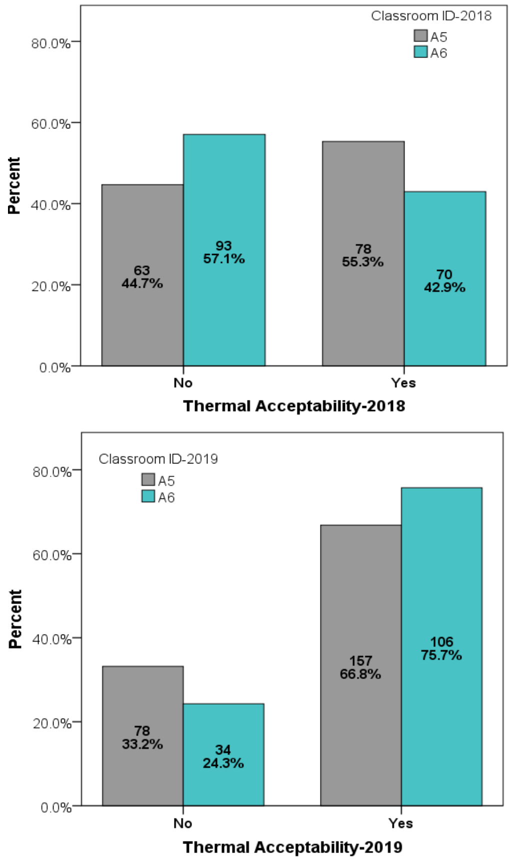


Figure 22. Thermal acceptability in A5 and A6 during winter and mid-season



Analysis of questionnaire data and responses to the direct acceptability question, it was shown that 70% of students were satisfied with the classroom thermal environment during mid-season 2019. In contrast, only 49% of respondents were satisfy during the survey in winter 2018. Based on indirect acceptability analysis using the percentage of students voted on the three categories of thermal sensation scale (Figure 19), 65% and 81% of students were considered to be comfortable, during winter and mid-season, respectively.

Direct thermal acceptability during winter period shows that a higher percentage of students in A6 were dissatisfied with the classroom temperature compared with percentage of dissatisfaction in A5 (Figure 22). In contrast, during mid-season (after installation of the ventilation) a higher percentage of students voted to be satisfied in A6 (classroom with ventilation) compared to A5 (classroom without ventilation).

The personal variables, namely metabolic rate, and clothing insulation are influencing how children feel about the thermal environment. Therefore, questionnaire asking whether students had a jumper or jacket at the time of the survey. This information can be used to estimate the clothing insulation level for further analysis. According to the responses, 91% of students wore jacket over their school uniform during winter survey period while 70% of them had jumper or jacket during mid-season.

Possible effects of tiredness on children’s responses were assessed using a three-point scale that ranged from ‘Very sleepy and tired’ to ‘Not tired and sleepy’ presented with the pictorial scale (Figure 23). It was custom designed for the purpose of this study, with a child’s facial and body expression indicating different levels of tiredness, seated in the classroom. The analysis results indicate that the level of tiredness was similar during winter and mid-season surveys. Over 50% of students were a bit sleepy and tired at the time of the questionnaire survey, while only about 28% of them were not tired or sleepy at the time of the survey.

Figure 23. Level of tiredness during winter (top) and mid-season (bottom)

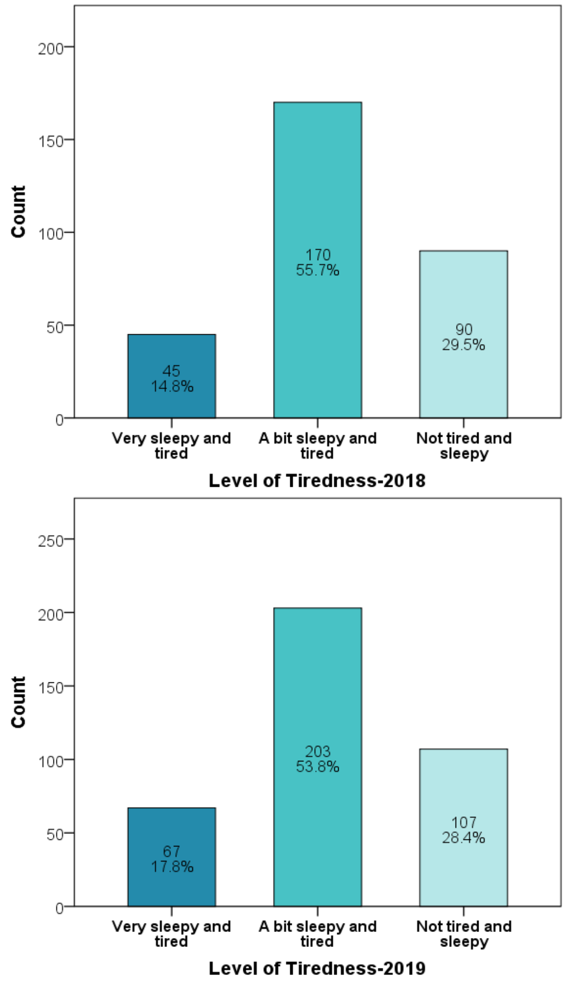


Figure 24. Level of tiredness during mid-season (bottom)

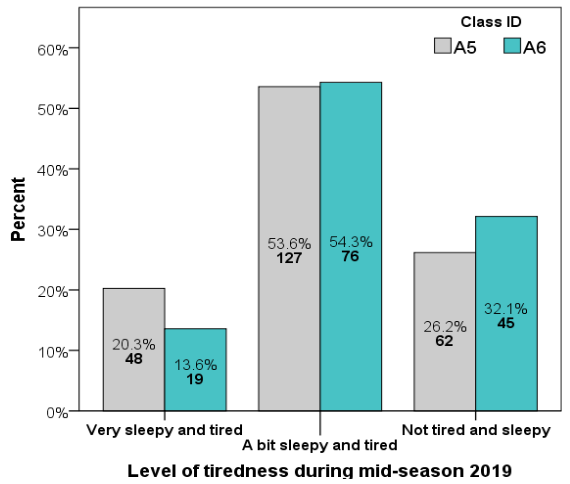
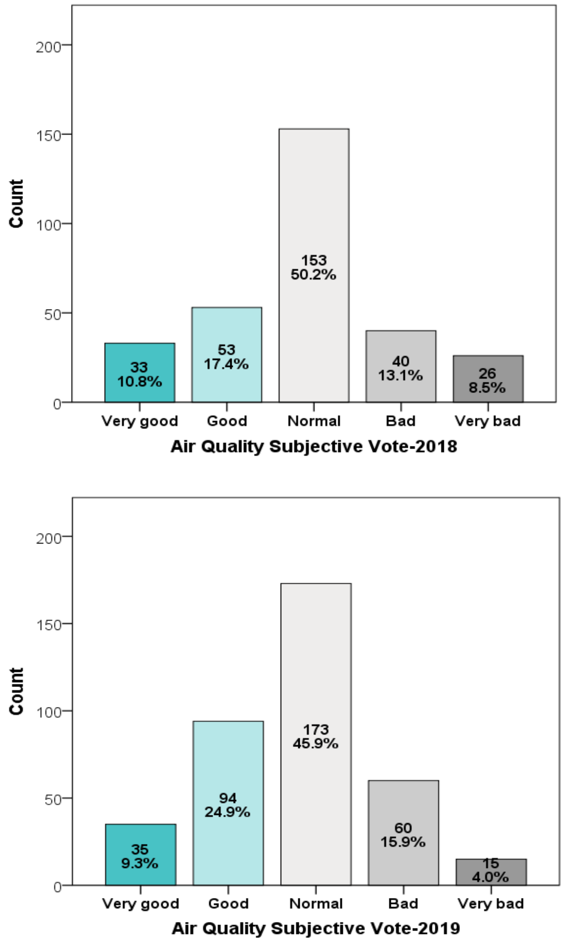


Figure 24 shows that during mid-season survey period the percentage of tiredness is lower in A6 (classroom with ventilation) compared with that in A5 (classroom without ventilation system).

According to students' responses to the questionnaire survey, air movement in the classroom was considered to be between still (49%) and mild (41%) during winter survey, while a higher air movement was noted during mid-season survey in 2019 (55% mild and 35% still).

Students also reported their perception of air quality at the time of survey (Figure 25). According to subjective votes of the students, air quality was considered normal by majority of students during both field work campaigns. A slightly higher percentage of satisfaction were observed during mid-season compared to winter period. The percentage of normal to very good votes on the classroom air quality was 78.4% and 80.1% during winter and mid-season, respectively.

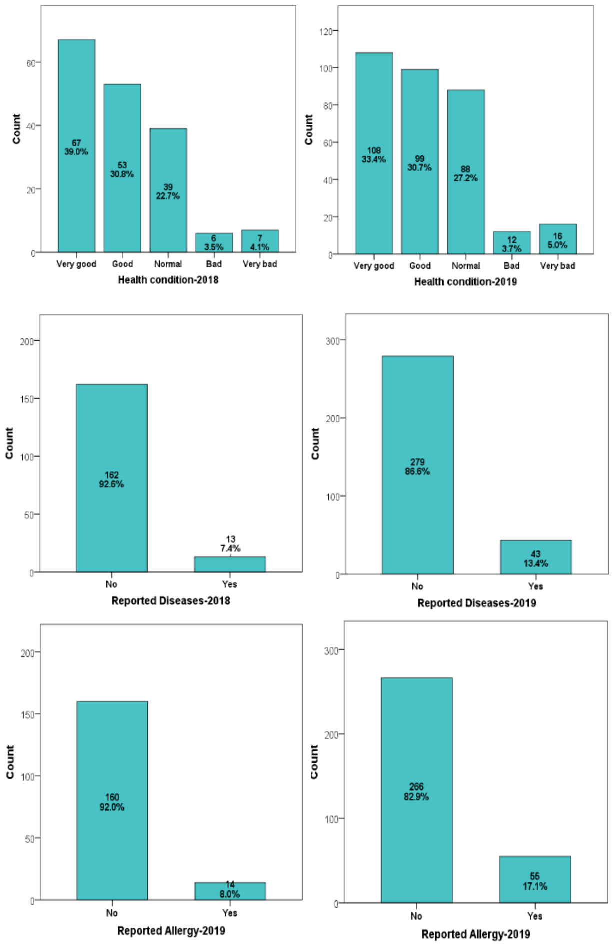
Figure 25. Perception of air quality during winter (top) and mid-season survey (bottom)



Students were in general in good health condition based on their report on the questionnaire survey, while only about 9% of participating students reported 'Bad' or 'Very bad' health condition. This is consistent with students' responses to the questionnaire in regard to the presence of disease being 7.7% in winter and 13.4% during mid-season survey period. About 3% of participating students reported to suffer from Asthma. As depicted in Figure 26,

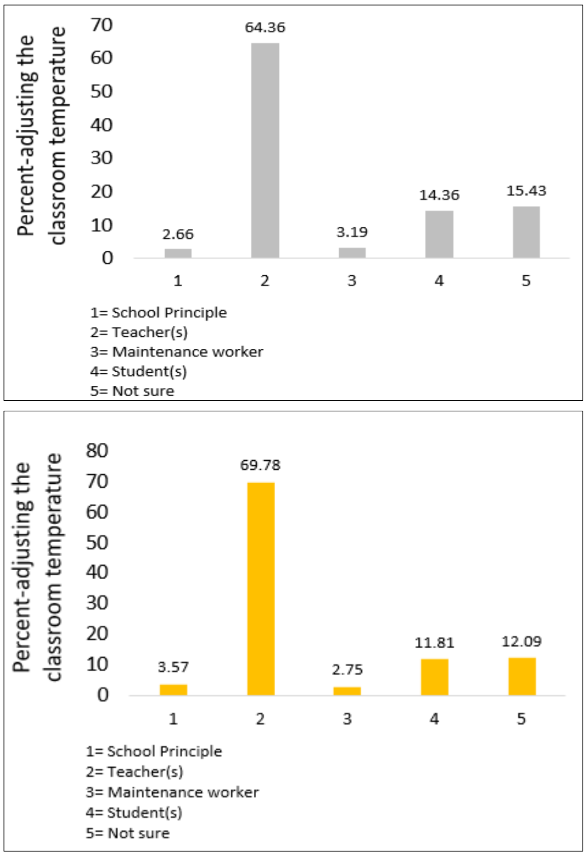
8% and 17% of students reported allergy during winter and mid-season survey, respectively.

Figure 26. Reported heath condition (top), disease (middle), and allergy (bottom)



Students were asked to respond to questions related to behavioural control and adjustments in the classrooms. According to students' responses, teachers are mainly responsible to adjust the classroom temperature (Figure 27). Analysis of children's responses in regard to adaptive behaviours and adjustments are provided in appendix 2 for winter 2018 and mid-season 2019 survey periods.

Figure 27. behavioural adjustments in the classroom during winter (top) and mid-season (bottom)



Classroom A6 (top) and A5 (bottom)

5. VOCs MEASUREMENT

Sulfur Volatile Compound and Volatile Organic Compound Analysis of Gas Samples were performed to compare the two classrooms with ventilation (A6) and without ventilation (A5) during normal occupancy period.

Sample Description

Sampling was performed on 13th and 14th May 2019 in two adjacent classrooms with and without ventilation system. Indoor air from two classrooms A5 and A6 was collected from the Senior Campus located in Maroubra. In total 12 samples, sorbent tubes, were collected and activities of classrooms were observed at the time of sampling. During the lessons, whiteboard markers were used (A6), and overhead projectors were operated when needed (A6 and A5). Windows and doors were kept closed during the sampling. In A6, shading device was partially operated in a few lessons to avoid glare, which covered the ventilator located on top of the windows.

Two samples were obtained during unoccupied condition as a base line for 30 minutes from 7:50 a.m. on 14th May 2019. Classrooms were not occupied for 15 hours before the sampling.

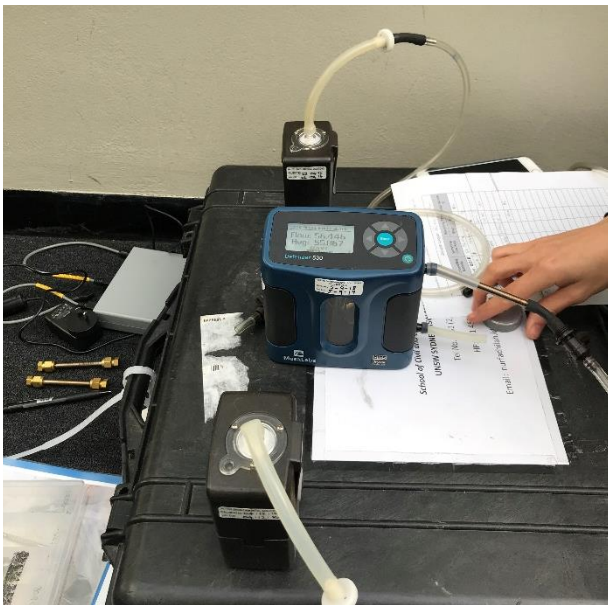
Methodology

For VOC analysis, the indoor air samples were collected on to Tenax™ TA sorbents (Markes International, UK) tubes at a sampling rate of about 60 mL/min for 30 minutes during the session periods using SKC AirCheck sampling pumps with flow reducers (Active Environmental Solutions, Australia). Sampling was performed 15 minutes after students entered the classroom.

An additional handheld volatile organic compound (VOC) MiniRAE 3000 device with photoionization detectors (PIDs) was used which is highly sensitive to low concentrations of VOCs. This was to get a general understanding of TVOC in the classrooms.

Sampling pumps and tubes used in classroom A5 (left) and A6 (right), MiniRAE 3000 PID sensor (right)

The sampling flows were calibrated using the DryCal Defenders (Mesalabs USA).



The sample tubes were analysed using thermal desorption – gas chromatograph – mass spectrometer (Unity II Thermal desorber Marks International, UK – 7890A GC + 5975C Agilent Technology, USA) [25]. Samples from tubes were desorbed at 275°C for 5 min and then pre- concentrated into a cold trap (U-T11GPC graphitized carbon analyte focusing trap) at -10°C. The trap was desorbed by increasing its temperature at a rate of 40°C/min to 290°C, and then holding at this temperature for 5 min. The GC was fitted with a DB-VRX (30 m 0.25 mm 1.4 µm) column (Agilent Technologies, USA) with helium as the carrier gas (flow rate of 1.6 ml/min, constant flow). The gas chromatograph column temperature was initially held at 50°C for 2 mins, raised at a rate of 15°C/min to 220°C and then held for 5 minutes. Total run time was 17 min. Temperature all other flow path was maintained at 175°C. The mass spectrometer was set at constant scan between 35-335 m/z (mass to charge ratio) with 2.50 min solvent delay, and the ChemStation (Agilent Technologies, USA) software suite was utilized for data acquisition. MS Source and Quadrupole temperatures were set at 230°C and 150°C respectively.

VOCs were identified by matching the mass spectrum of each chromatography peak against the NIST Standard Reference Database (Version 17.0). The detection of a compound was reported when the match quality was greater than 80. VOC concentrations were calculated from the integrated area of the peak (i.e. the abundance of total ions under the peak) using the corresponding calibration curves from TO15 calibration gas mixtures. The concentrations of VOCs that did not have their own calibration curves were calculated using a toluene calibration curve.

Results of VSCs and VOCs Analysis

The results of VOCs analysis of the indoor air samples supplied to the laboratory are summarised in Table 1 which shows A6 in general has significant improvement in VOC level.

All detected VOCs are well below the 8-Hour Time Weight Average limits recommended in the Work Place Exposure Standards for Airborne Contaminants [26]. There is unknown compound (which was not identified using MS library or within the list of mixed gas calibration standard (TO15 calibration standard). It occurred at a very high concentration in air sample on 14th May from 08:45 a.m. in both rooms and l detected in room A5 until 14:25 p.m., while it was not detected in classroom A6. Due to limited sampling replicates, it was not possible to identify the unknown compound using the GC-QTOF which is based on the mass accuracy.

13th May 2019

During the first day classrooms were occupied by 15-25 students. The occupancy profile and lesson timing were similar during the measurements. Students in both classrooms used their laptops for the classroom activities in the afternoon class. In the morning lessons, teachers used projectors and whiteboard marker in A6 and A5, respectively. Windows and doors were kept closed during the lessons.

Figure 28. Detected compound in A5 and A6 from 11:40 a.m. for 30 minutes

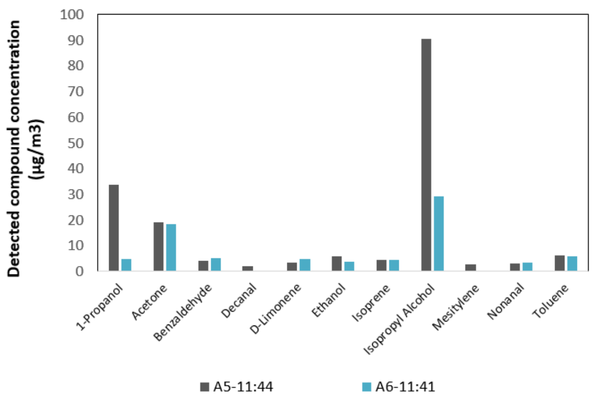


Figure 29. Detected compound in A5 and A6 from 12:40 for 30 minutes

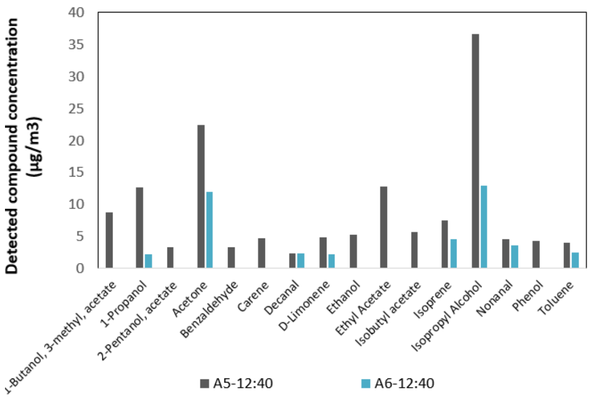
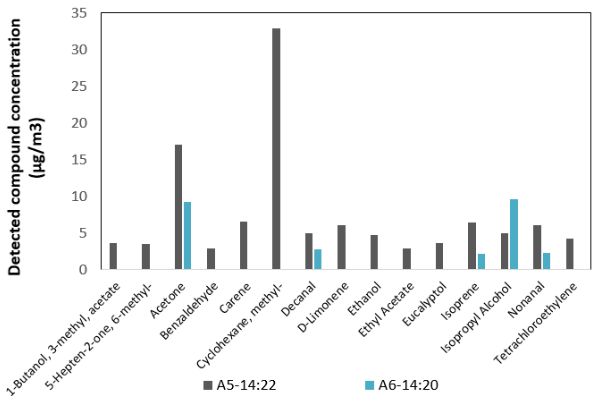


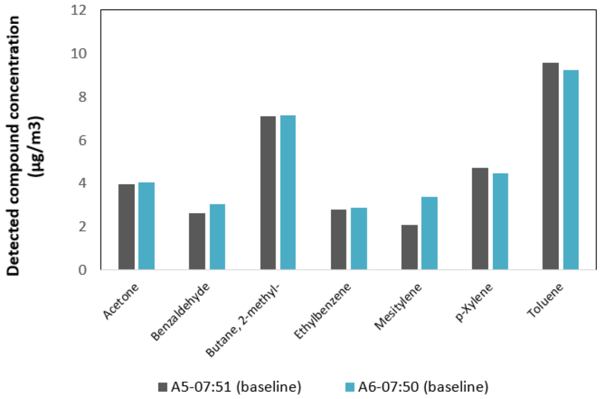
Figure 30. Detected compound in A5 and A6 from 14:20 p.m. for 30 minutes



14th May 2019

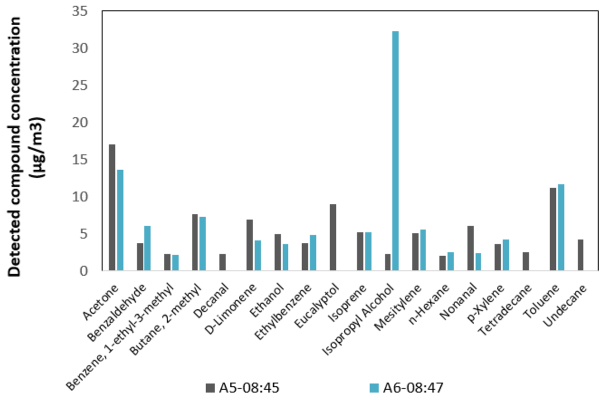
Air samples were collected during unoccupied condition in the second day in the morning before lessons started. Both classrooms show similar level of compounds and concentration during unoccupied condition.

Figure 31. Detected compound in A5 and A6 from 7:50 a.m. for 30 minutes (baseline)



During the second day morning air sampling in A6, classroom was occupied by 19 students and both whiteboard markers and overhead projector were used during science lesson and thus sampling period. At the same time, blinds were closed to avoid glare during the classroom activity which reduced the efficiency of the ventilator to provide fresh air. This likely explains higher level of compounds during this period in A6 compared to other sessions. Isopropanol also known as isopropyl alcohol, is one of the main chemicals found in dry-erase markers. Inhaling the emissions of a dry-erase marker can cause both long-term and short-term health related problems which highlights the importance of proper ventilation in schools. During this experiment in the second, A5 had 18 students and lesson was only involved reading and writing.

Figure 32. Detected compound in A5 and A6 from 8:45 a.m.



During afternoon air sampling in A5, teacher was not willing to keep the windows closed (classroom without ventilation). However, for 30 minutes sampling door and windows were kept closed. No whiteboard marker and video/projector were used. A5 was occupied by 13 students and A6 had 18 students during the afternoon experiment. In A6, white board marker was used.

Figure 33. Detected compound in A5 and A6 at 14:25 a.m.

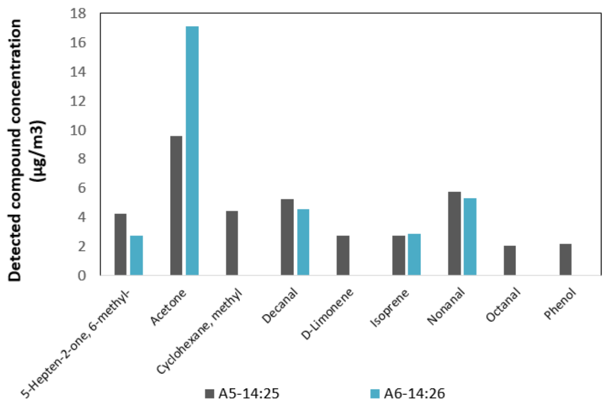


Figure below shows the unknown compound which was very high in the morning in both classrooms, mainly in A5 (classroom without ventilation system). This compound was reduced in the afternoon in A5 and disappeared in A6.

Figure 34. Unknown compound detected in A5 and A6

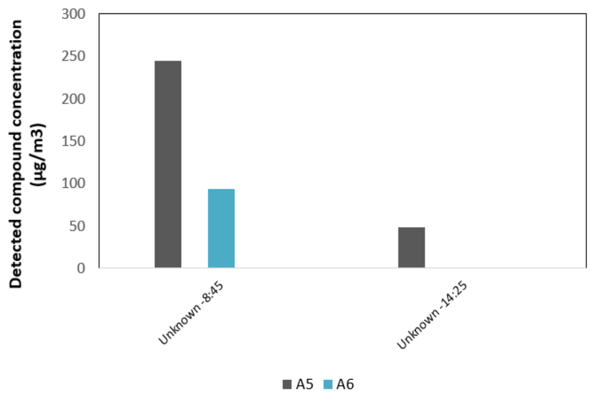


Table 2. VOC Analysis Results –detected compound concentration (µg/m3)

Compounds	Room A5 - No Ventilation						Room A6 with Ventilation					
	13-May			14-May			13-May			14-May		
	1144 HRS	1240 HRS	1422 HRS	0751 HRS*	0845 HRS	1425 HRS	1141 HRS	1240 HRS	1420 HRS	0750 HRS*	0847 HRS	1426 HRS
1-Butanol, 3-methyl-, acetate	-	8.72	3.59	-	-	-	-	-	-	-	-	-
1-Propanol	33.8	12.62	<2	-	-	-	4.68	2.17	-	-	12.35	24.23
2-Pentanol, acetate	-	3.26	<2	-	-	-	-	-	-	-	-	-
5-Hepten-2-one, 6-methyl-	-	-	3.47	-	-	4.26	-	-	<2	-	-	2.74
Acetone	19.07	22.46	17.09	3.94	17.04	9.56	18.34	11.93	9.27	4.04	13.56	17.09
Benzaldehyde	4	3.23	2.91	2.63	3.72	<2	5.2	<2	<2	3.05	6.03	<2
Benzene	<2	<2	<2	<2	<2	<2	<2	<2	-	<2	2.46	-
Benzene, 1,2,3-trimethyl-	-	-	-	<2	-	-	-	-	-	<2	-	-
Benzene, 1,2-dichloro-	-	-	<2	-	-	-	-	-	-	-	-	-
Benzene, 1,3-dichloro-	-	<2	-	-	<2	-	-	-	-	<2	2.58	-
Benzene, 1,4-dichloro-	<2	-	-	<2	-	-	<2	-	-	-	-	-
Benzene, 1-ethyl-3-methyl-	<2	<2	-	<2	2.21	-	<2	-	-	<2	2.19	-
Butane, 2-methyl-	-	-	-	7.1	7.59	-	-	-	-	7.13	7.28	-
Carene	<2	4.72	6.49	-	-	<2	-	-	-	-	-	-
Cyclohexane, methyl-	<2	-	32.88	<2	<2	4.43	<2	-	<2	<2	<2	-
Decanal	2.07	2.3	4.95	-	2.21	5.22	<2	2.26	2.8	-	<2	4.58
Decane	-	-	-	-	<2	-	-	-	-	<2	-	-
D-Limonene	3.51	4.86	6.03	<2	6.88	2.72	4.6	2.11	<2	<2	4.09	<2
Ethanol	5.74	5.2	4.7	-	4.99	<2	3.81	-	<2	-	3.67	4.92
Ethyl Acetate	-	12.78	2.84	-	-	-	-	-	-	-	-	-
Ethylbenzene	<2	-	-	2.79	3.72	-	<2	-	-	2.88	4.85	-
Eucalyptol	-	-	3.64	-	9.03	<2	-	-	-	-	-	-
Heptane	<2	-	-	<2	<2	-	<2	-	-	<2	2.92	-
Isobutyl acetate	-	5.72	<2	-	-	-	-	-	-	-	-	-
Isoprene	4.49	7.41	6.36	-	5.25	2.73	4.55	4.54	2.15	-	5.22	2.84
Isopropyl Alcohol	90.54	36.67	4.96	-	2.21	-	29.18	12.9	9.6	-	32.32	75.53
Mesitylene	2.52	<2	<2	2.06	5.07	-	<2	-	-	3.37	5.56	-

Compounds	Room A5 - No Ventilation						Room A6 with Ventilation					
	13-May			14-May			13-May			14-May		
	1144 HRS	1240 HRS	1422 HRS	0751 HRS*	0845 HRS	1425 HRS	1141 HRS	1240 HRS	1420 HRS	0750 HRS*	0847 HRS	1426 HRS
n-Hexane	<2	<2	-	<2	2.04	-	<2	-	-	2.12	2.47	-
Nonanal	2.92	4.57	6.06	<2	6.04	5.77	3.42	3.51	2.26	2.27	2.4	5.29
Nonane	<2	-	-	<2	<2	-	<2	-	-	-	<2	-
Octanal	-	-	-	-	-	2.02	-	-	-	-	-	-
o-Xylene	<2	<2	-	<2	<2	-	<2	-	-	<2	<2	-
Pentane, 2-methyl-	<2	-	-	<2	<2	-	-	-	-	<2	<2	-
Phenol	-	4.28	-	-	-	2.2	-	-	-	-	-	-
p-Xylene	<2	<2	<2	4.71	3.66	-	<2	<2	<2	4.45	4.28	-
R(-)3,7-Dimethyl-1,6-octadiene	-	<2	<2	-	<2	-	<2	<2	-	-	<2	-
Tetrachloroethylene	-	-	4.23	<2	<2	<2	-	-	<2	<2	-	-
Tetradecane	-	-	-	-	2.54	-	2.41	-	-	-	-	-
Toluene	6.24	4.01	<2	9.58	11.14	-	5.78	2.39	<2	9.23	11.67	-
Undecane	-	-	-	-	4.25	-	-	-	-	-	-	-
Unknown**	-	-	-	-	244.2	48.05	-	-	-	-	93.39	-

- : Not detected
<2 detected but below the limit of quantitation
*: base line
**: unknown compounds

6. INFILTRATION AND VENTILATION RATE MEASUREMENT

The experiment was performed in the classroom A6 on Thursday 11th October 2018 from 9:00 to 18:00. The classroom was not occupied for two weeks before the experiment. Therefore, the classroom was not affected by any emissions except those from the environment.

The selected classroom (A6) is 6.0 m * 7.8 m * 3.0 m. Windows are placed in the walls along the width of the classroom. Classrooms are normally used by students seated more than 90% of the time. A height of 1.2 m above the ground was defined corresponding to the level of seated students.

This system is bundled in a system solution and includes the Innova 1403, the Innova 1412i Photoacoustic Gas Monitor, and 7650 Application Software. The Innova 1403 delivered SF6 (Sulphur Hexafluoride) to help measure the effectiveness of a ventilation system.

The experiment was conducted with two approaches.

1) First approach (SIT-A) evaluates the infiltration rate of the classrooms. It highlights the level of permeability of the envelope by the existing leakages and defects created along the construction phase or during its life mostly due to the aging of the building. The infiltration mostly happens through the building envelope where air moves energy from the indoor space to the outer side of the building and vice versa providing an uncontrolled energy waste in conditioning the inner space.

This study aims to evaluate the air changes through the walls and openings which are in a direct contact with the outdoor air and environment. Nevertheless, air change process could also happen in the corners of classrooms and those surfaces placed on the top or below (or rooftop or basement in this case). For this purpose, all the doors and windows were kept closed in order to focus only on the leakages providing or exhausting air to/from indoors. No other ventilation systems existed within the building. Heating was provided by a single split-type heat pump placed outside the classroom. Another thermal split-convector was placed in the classroom; however, it was disconnected and sealed.

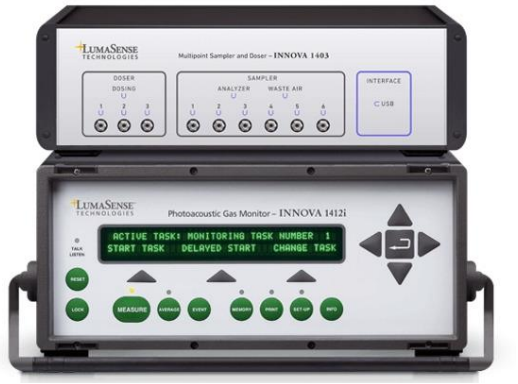
2) The second approach (SIT-B) was to evaluate the impact of natural ventilation in the classroom. This was performed in two different settings. The first test setup was aiming to evaluate the impacts of one open window in the natural ventilation process in the classroom. The second method assessed the ventilation rate when all windows and door connected to the outdoor space were kept opened. Natural ventilation was affected by wind and pressures differences.

Test set-up

These tests were highly affected by the weather conditions, in particular wind velocity.

A reference Sampling Point (SP) centred in the room was defined while the rest of the SP were regularly placed along the classroom. This reference SP was named as SP0 and used as a comparative factor between different essays in order to relate the results obtained at different times and weather conditions.

A total of 13 SP were placed along the classroom in three different steps. The equipment composed by the SF6 gas cylinder and the Sampling and Doser (INNOVA 1412i and INNOVA 1403, LUMASENSE Technology) were placed in a corner of the classroom while three different Dosing Points (DP) were placed in the other corners which serve to dose the gas in the classroom air. Each dosing tubing was mounted to a mixing fan that helped to diffuse the gas concentration in the classroom. Fans were used during the dosing stage and they were stopped when the decay concentration sampling started. The sampling was started when the gas concentration was completely diffused and homogeneously distributed along the classroom by observing and monitoring the real-time data.



The INNOVA 1403 multipoint gas sampler and doser for air-exchange and flow analysis.

All the fans were plugged to the same electrical distributor commanded by a switch for each fan in order to manage them simultaneously. The gas Dosing and Sampling equipment were connected to the gas cylinder and all the tubing were joined to the Dosing and Sampling nozzles.

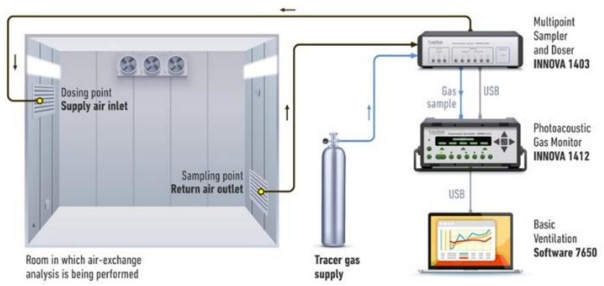
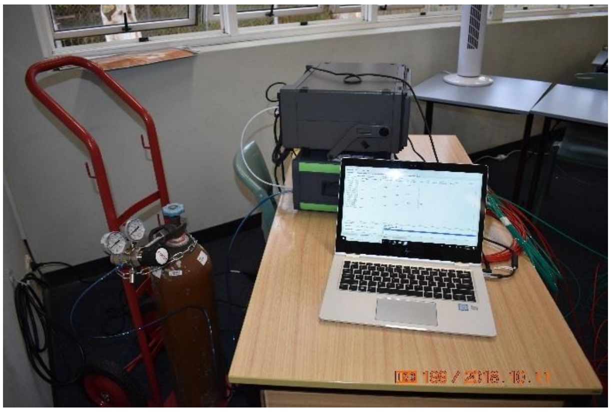


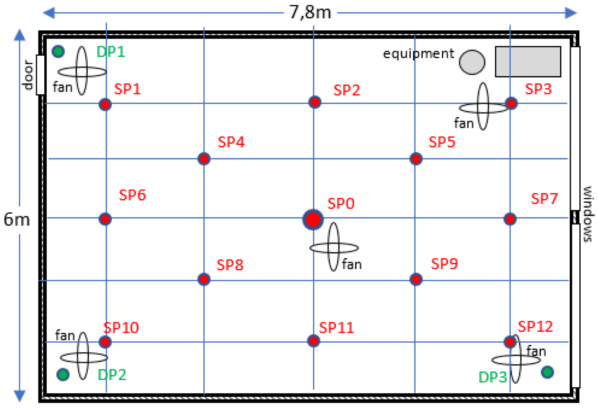
Diagram illustrating the connections between Cylinder and tracer gas: http://trends.directindustry.es/lumasense-technologies/project-4798-166464.html



Methodology

The methodology was as follows:

- All the windows and the door were closed.
- The SF6 gas cylinder valve was opened till reaching a pressure of 300kPa ±10% within the gas regulator.
- All the fans were on while dosing phase was active. They were shut down seconds before the decay concentration measurement was started.
- Three dosing flow phases (one for each dosing point) were set up.

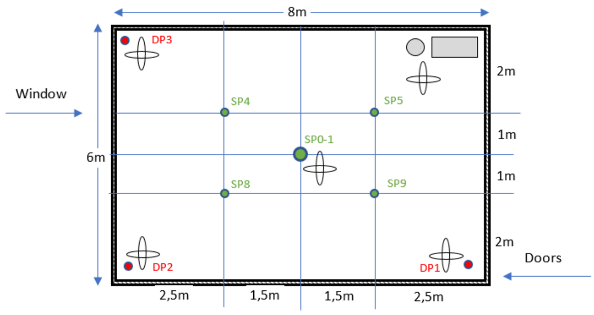


DP: dosing points
SP: sampling points

<u>Closed windows test</u>

The test was started in the first stage placing the Sampling Points named as SP4, SP5, SP8, SP9 and SP0-1 (Figure 35). The last point corresponded to the reference node for the first stage. Outdoor wind velocity was measured at the start of the test reaching 2.6 m/s; however, it was continuously changing during the tests.

Figure 35. Stage 1



Reference Sampling Point (SP0-1) centred in the classroom

Maximum SF6 concentration for the classroom was estimated in 10 ppm. The concentration decay method measurement started when all the SPs reach a similar concentration over 10 ppm. 120 seconds for each gas dosing stage was considered to be enough to provide a well-mixed concentration along the classroom. The SF6 gas flow was calculated to be 4.68 ml/s, including a 20% of gas lost through the leakages in the classroom while the equipment was dosing until the total concentration was reached. As infiltration exchanges air with the outer air continuously, we consider an extra 20% volume that can be lost before the test starts.

- The equations given below were used to calculate the total dosing flow:

a. Select dosing timing between T_{max} and T_{min}:

- $T_{max}[s] = \frac{V_{air}[m^3]*m*C[ppm]}{1{,}58\left[\frac{ml}{s}\right]} = \frac{140{,}4*1{,}2*10}{1{,}58} = 1066\ [s]$
- $T_{min}[s] = \frac{V_{air}[m^3]*m*C[ppm]}{17{,}46\left[\frac{ml}{s}\right]} = \frac{140{,}4*1{,}2*10}{17{,}46} = 97\ [s]$

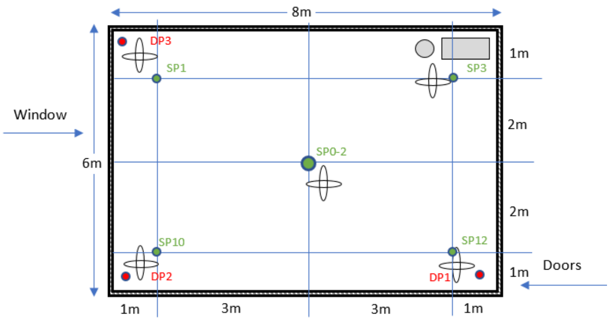
b. Once the timing is selected, 360 s was selected here (120 s each phase), the dosing flow (F_{SF6}) is derived:

- $F_{SF6}\left[{}^{ml}/_{s}\right] = \frac{V_{air}[m^3]*m*C[ppm]}{T[s]} = \frac{140,4*1,2*10}{360} = 4,68\ [{}^{ml}/_{s}]$

A total volume of 1.685 l of SF6 gas was provided. The mean starting measured concentration was 11.19 ppm and end point of 1.98 ppm. The test took 2.23 hours to be completed. A reference n-value of 0.81 h^{-1} in SP0-1 and an average of 0.78 h^{-1} for all the Sampling Points were obtained.

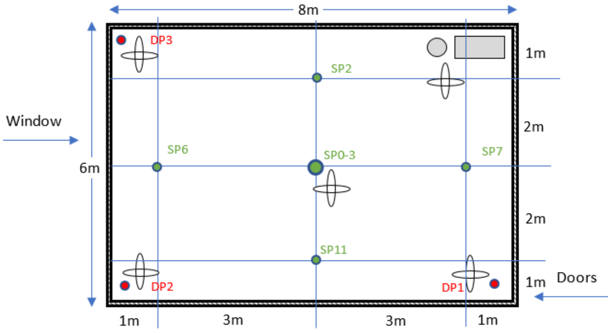
The second stage required to place SP1, SP3, SP10, SP12 and SP0-2 (Figure 36). Outdoor wind velocity was 3m/s at the time of measurement. The same concentration as used in the previous stage was considered, obtaining a mean starting measured concentration value of 10.53 ppm and end point of 2.02 ppm. The concentration decay method measurement started when all the SPs reach a similar concentration over 10 ppm. The test took 1.75 hours to be completed. A reference n-value of 0.96 h^{-1} in SP0-1 and an average of 0.95 h^{-1} for all the Sampling Points were obtained. In this case, the test was shorter because a well-developed decay concentration was reached.

Figure 36. Stage 2



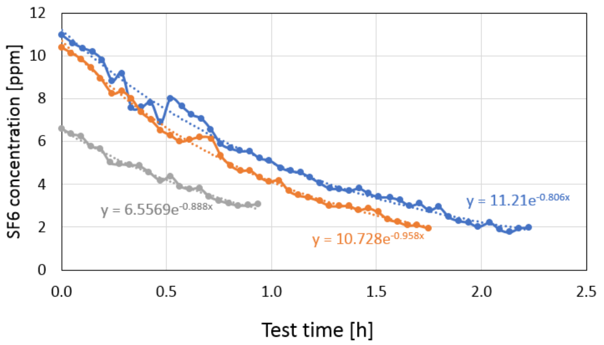
The third stage involved the following points SP2, SP6, SP7, SP11 and SP0-3 (Figure 37) to evaluate the whole classroom, increasing the accuracy of the results. In this case, due to lack of time, the test was shorter reducing the starting gas concentration to a mean top value of 6.68 ppm and end point of 2.90 ppm in 0.94 hours. The concentration decay method measurement started when all the SPs reach a similar concentration over 6 ppm. A reference n-value of 0.89 h^{-1} in SP0-3 and an average of 0.89 h^{-1} for all the Sampling Points were obtained. Wind speed outside of the classroom was 1 m/s during this test.

Figure 37. Stage 3



The graph given below (Figure 38) shows the decay concentration for each of the three reference SPs (SP0-1 (blue), SP0-2 (orange) and SP0-3 (grey)) and includes the equations that define the log law which rules the decay method theory.

Figure 38. Decay concentration for each of the three reference sampling points



The following graph (Figure 39) shows the representation of the test results trend. All the concentration points were evaluated as they were obtained in one single phase resulting in a single trend line and scale which was corrected to be a e-based logarithmic. This was to develop a straight line with a slope which gives the average n-value of 0.86 h^{-1} for the reference Sampling point (SP0). The rest of the SPs are related in the next chart.

Figure 39. Decay concentration for the reference sampling point

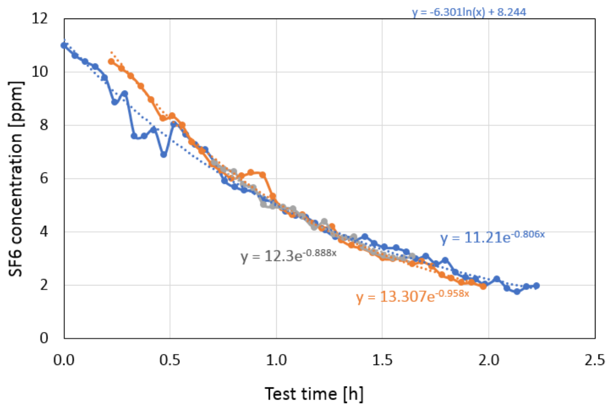


Figure 40. Decay concentration against time

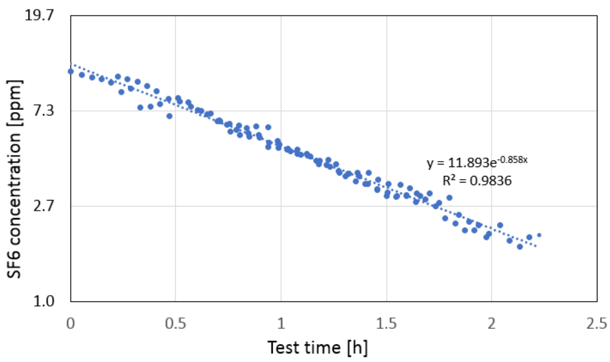


Table 3. ACH per sampling point

	Cmax [ppm]	τmax	Cmin [ppm]	τmin	Δτ	Δτ [h]	ACH [1/h]
SP1	10.57	14:06:12	2.05	15:53:55	1:47:43	1.80	0.91
SP2	6.90	16:19:12	2.80	17:15:49	0:56:37	0.94	0.96
SP3	10.19	14:12:19	1.98	15:54:29	1:42:10	1.70	0.96
SP4	11.36	10:16:11	1.98	12:29:45	2:13:34	2.23	0.78
SP5	11.15	10:16:45	1.80	12:30:19	2:13:34	2.23	0.82
SP6	6.71	16:20:50	2.89	17:16:56	0:56:06	0.94	0.90
SP7	6.58	16:20:17	3.03	17:16:23	0:56:06	0.94	0.83
SP8	11.26	10:17:18	2.07	12:30:52	2:13:34	2.23	0.76
SP9	11.21	10:17:51	2.09	12:31:25	2:13:34	2.23	0.75
SP10	10.79	14:07:18	2.37	15:52:15	1:44:57	1.75	0.87
SP11	6.61	16:21:23	2.70	17:17:29	0:56:06	0.94	0.96
SP12	10.71	14:07:52	1.74	15:52:49	1:44:57	1.75	1.04

Opened windows test

These two tests were carried out based on the same protocol described previously. However, the gas dosing phase and the measurements were shorter. This test had two stages: the first test was evaluating the natural exchange through one window opened directly to the outdoor, and the second test performed with the opening of all the windows opened to the outdoor space. All the fans were on and windows were closed while dosing phase was active. Fans were shut down and the windows were opened a few seconds before starting the decay concentration measurement.

First test was conducted after the first stage for the analysis of the closed window test, using the residuary concentration remaining in the classroom, thus a smaller quantity of air dosing was required. The same SPs used in the first stage of the study were used (SP4, SP5, SP8, SP9 and SP0) to reduce the test setup time. The concentration decay method measurement started when all the SPs reached a similar concentration of 11 ppm. A starting point of 10.83 ppm concentration was obtained. The test was finalized once the mean concentration was below 1.93 ppm. The test took 0.75 hours to be completed. A reference n-value of 2.35 h^{-1} in SP0 and an average of 2.28 h^{-1} for all the Sampling Points were obtained. It was observed that all points obtained a similar value of the air change rate. They were all distributed in the central area of the classroom, so it was understood that the air change pattern inside the classroom was homogeneous.

The second test was done after completion of the last stage of the closed window tests, using the same position of the Sampling Points (SP2, SP6, SP7, SP11 and SP0). This test evaluated natural ventilation of the classroom when all the windows and door were opened, creating an air movement through the door placed in the opposite wall of the classroom. The concentration decay method measurement started when all the SPs reached a similar concentration over 5 ppm. The starting point of mean concentration was 5.29 ppm. The test was finalized once all the concentration rates below 0.05 ppm. The test took 0.23 hours to be completed. A reference n-value of 21.07 h^{-1} in SP0 and an average of 21.75 h^{-1} for all the Sampling Points were obtained. In this case, a higher air change rate (25.04 h^{-1}) was observed in the SP2 point, which was closer to the air movement generated between the windows and the door, which was affected to the air change pattern inside the classroom.

7. INTRODUCTION TO HEALTHBOX 3.0

With Healthbox 3.0 [27], the classroom is ventilated in an energy efficient way, giving students and teachers a healthy indoor climate:

• Protection against excessive moisture concentrations

• Supplied with good air quality

Fresh air is supplied in dry rooms via the discrete Invisivent window ventilation. The polluted air is removed through Healthbox 3.0. The built-in central sensors continuously monitor the moisture level, CO2 and/or VOC (volatile organic substances or 'odors'). When the air quality in a certain space decreases, Healthbox 3.0 immediately adjusts.

The concept of ventilation system provided by RENSON is given in the diagram below (Figure 41) which includes three parts: a) Self-regulating window vents, b) Ventilative cooling, c) Extraction of air.

Figure 41. Ventilation system working diagram

PRODUCT DESCRIPTION

The system is a fan unit for demand-driven mechanical air extraction with individual detection and extraction per room via control modules. The electronically controlled control modules are located externally on the motor unit and are controlled and powered directly from the motor unit.

USE

The fan unit has been developed for the controlled central extraction of used air in a room and is an integral part of the energy-saving C+ ventilation system.

Optimum operation of the C+ ventilation system is ensured when the following three matched components are present:

Supply: Self-regulating window fans (class P3 or P4)

Lead-through:25 m³/h at 2 Pa - 50 m³/h at 2 Pa

Extraction:

- Fan unit: motor unit with central fan + electrically controlled control modules
- Air ducts: Easyflex – best airtightness class D – material PE
- Blow-off: roof/gable lead-through with low pressure loss

FEATURES

Electrically controlled control modules (transparent):

- **Automatic demand-driven extraction**
- **Electronic sensors:** measure indoor air quality 24 hours a day in the extracted air flow. The plug-in PCB with sensor(s) is placed on the PCB of the control module via a plug & play connector.
- **Air extraction control module:** automatic control that will extract air depending on the measured air quality:
  - Absolute CO_2 detection: proportional control depending on the CO_2 level
  - Dynamic & absolute moisture detection: dynamic and proportional control depending on the course of the relative and absolute humidity
  - Dynamic VOC detection: dynamic control depending on the course of the VOC level
  - Combination of dynamic & absolute moisture detection and dynamic VOC detection
- **Elliptical valve blade:** ensures additional quiet operation
- **Valve collectors:** possibility of connecting up to 3 control modules to 1 intake point of the motor unit. Two valve collectors allow up to 11 rooms to be connected to the motor unit for individual detection and control of air extraction.

The valve collectors can be placed either at the motor unit or decentrally (air duct between valve collector and motor unit), to deal with air ducts in small spaces in a smart/compact way. Electrically connect the valve collector to the motor unit via RJ45 patch cable.

Motor unit (blue/white):

- **Connection of control modules**: plug & play external fixed connection of electrically controlled control modules.
- **Automatic calibration**: takes place in 2 stages:

- Stage 1: pressure drop readings taken automatically in all air ducts

- Stage 2: fan speed and individual valve position per control module calculated automatically for nominal air extraction.

- **Fan with EC motor**: ø180 impeller (galvanized steel) for extremely quiet and energy-efficient operation

- **Fan control**: active variable pressure control: continuous speed control of the fan to achieve the required air extraction per room at the lowest possible pressure level (always blade fully open from 1 control module).

- **Breeze function**: temporary nominal ventilation (demand control deactivated) at times when there is a given cooling need (=> optimum shading factors)

- Can be combined with flat aluminium extraction grilles without control valve, as an outlet point in the room

SmartConnect:

- **Ethernet connection**: wired connection to router via UTP cable

- **USB Wi-Fi dongle**: Wi-Fi connection to router and installation app

- **Digital communication**:

- Communication with the building occupants: via 'resident' app and web portal

- Communication with the installer: via installer app and web portal

- Communication with automation system: via API and/or via switch module (3 contacts)

- '**Resident' app**: read real-time/history of air quality and ventilation level in the entire place, down to room level. Colours give an indication of the air quality per room. Setting of ventilation profiles.

- '**Installer' app**: guide through the installation process: start calibration with display of remaining time, display of installation parameters and enter measurement results for automatic layout of the measurement report, readout of pressure loss per connected air duct.

- **Automatic software update**

- **Fault indication via the installer and resident apps**

SPECIFICATIONS

- **Dimensions of fan unit**:
  - Without control modules:
    390 x 443 x 200 mm (L x B x H)
  - With control modules:
    567 x 567 x 200 mm (L x B x H)
- **Maximum fan operating pressure**: 350 Pa
- **Extraction rate of fan unit**:
  - 475 m³/h for 135 Pa suction head
  - 430 m³/h for 200 Pa suction head
-

Table 4. Specifications of the ventilation system

Extraction rate	**Electric power consumption**	**Sound power level [LWA]** Reference point according to Ecodesign
150 m³/h	28 W	32 dB(A)
225m³/h	35 W	34 dB(A)
325 m³/h	53 W	39 dB(A)
400 m³/h	80 W	43 dB(A)
475 m³/h	85 W	47 dB(A)

- **Fire prevention**: at an observed temperature >70 °C, depressurise the fan unit with each control module closed.

OPERATION

Possibility of (temporary) manual adjustment of the ventilation extraction rate can be done via operation.

- Via potential-free 3-position switch (XVK3) - wired

- Via the resident app (ventilation extraction rate can be set up to room level)

RESIDENTIAL REDUCTION FACTORS

- The fan unit is included in the EPB product database – FAN AND VENTILATION GROUP

- The fan unit is included in the EPB product database – DEMAND-DRIVEN VENTILATION SYSTEMS (EPW)

- The fan unit can be used in 4 configurations according to the provisions of the flat-rate table: The following table gives an overview of the available configurations and their validation within the flat-rate table:

Table 5. Configurations of the ventilation system

Configuration	$f_{reduc,vent,}$	
	Heat	Cool, Overheat
Configuration of Smartzone 0.43	0.43	1.00*
Configuration of Smartzone 0.50	0.50	
Configuration of Smartzone 0.61	0.61	
Configuration of Smart 0.90	0.90	

* = Breeze function. Entry in EPB software: the system has a bypass: YES

COMBINABLE PRODUCTS

- **Extraction in dry rooms**: control module for ventilation extraction in dry rooms (CO_2 control)

- **Apply design extraction grille** (with/without butterfly valve):

- Ø 80, 134 x 134 mm or Ø 125, 174 x 174 mm
- built-in or surface-mounted 11 mm

• **Easyflex air ducts**: ducts for air transport, best airtightness class D

• **Invisivent® COMFORT**: best air quality in each room (applicable in configuration with reduction factor 0.43, 0.50 and 0.61)

COMBINABLE PRODUCTS

• **3-Concentric chimney:** combination solution for collective ventilation extraction and flue gas supply and extraction

• **Extractor hood:** motorless hood coupled to the fan unit to extract smells

COMMUNICATION

Via the SmartConnect connection, Healthbox 3.0 can be connected to the internet. This allows Healthbox 3.0 to communicate with the user via a free app, and also with other smart devices in smart management systems.

HEALTHBOX 3.0 OPERATION

Healthbox 3.0 was specifically developed for integration in residential buildings but can also be used in the non-residential sector. It is a compact device, which means that it does not require a lot of installation space.

Proper functioning of the demand-controlled ventilation system is only guaranteed if the following three pillars are adapted to one another:

• Supply: self-regulating RENSON® window ventilation class P3 or P4.

• Throughput: door grille or crack under the door.

• Drainage: Healthbox 3.0 demand-controlled fan unit.

Demand-controlled ventilation:

The demand-controlled ventilation system from Renson® is successful due to its comfort, energy efficiency and ease of maintenance. The room is optimally ventilated according to the occupants.

Healthbox 3.0 monitors the air quality 24 hours a day for CO_2 or moisture and/or VOCs (odour) per connected room. The ventilation level is hereby intelligently fully automatically adjusted in function of the measured air quality. This is done based on sensors in the control module. As long as the air quality in a room is good, the ventilation level remains limited, which is important regarding energy in terms of heat savings and electricity consumption.

Fan control:

The fan is controlled via an active variable pressure control. This is a smart control that continuously adjusts the fan speed to achieve the required ventilation air flows at the lowest possible pressure level. This ensures extremely quiet operation as well as the lowest power consumption.

Breeze function:

Healthbox 3.0 is standard equipped with a Breeze function. The Breeze function helps to limit the risk of overheating.

When a cooling requirement is detected and the outdoor climate permits this, the demand-controlled ventilation is deactivated. All connected rooms are ventilated at a higher flow rate (nominal flow rate). This way, a ‘Breeze’ of fresher outdoor air is brought into the room.

When the occupant sets the Breeze function to ON via the app, this function automatically activates at night (between 0h and 6h) if the average indoor temperature (measured on all control modules) is higher than the minimum temperature (e.g. 24°C). The minimum temperature is freely adjustable in the app.

SMARTCONNECT

With the SmartConnect connection, Healthbox 3.0 can be connected to the school network. This offers the occupant the following benefits:

• School network **connected** to the internet:

— The app can be used to visualise data about the measured air quality from the device and if necessary, to temporarily manually adjust the ventilation level where necessary.

— The Lio web portal can be consulted.

— Healthbox 3.0 can be incorporated into a smart management system in order to communicate with other smart devices. All possibilities for interaction can be fully used.

• School network **not connected** to the internet:

— Healthbox 3.0 can be incorporated into a smart school to communicate with other smart devices in a management system. Interaction possibilities are rather limited.

Healthbox 3.0 works completely autonomously if it is not connected to the school network.

Connecting Healthbox 3.0 to the network

To use the app and the web portal, the network to which Healthbox 3.0 is connected must be connected to the Internet. This way, it is possible to read out all data from the ventilation system on the app, in order to adjust Healthbox 3.0 with the app.

Possible ways to connect Healthbox 3.0 to the school network are as follows:

- Network cable
- Ethernet-over-Power (EoP)
- Wi-Fi dongle

HEALTHBOX 3.0 APP

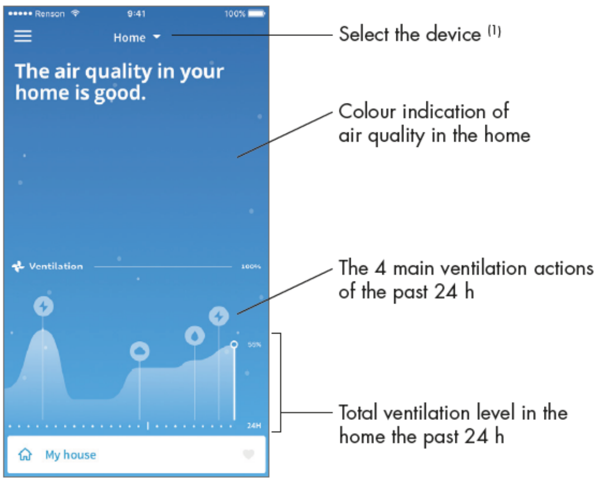
Download

The Healthbox 3.0 app can be downloaded for free from the App Store (Apple) or Google Play (Android). Register to create an account and discover all the benefits of this demand-controlled system. The Healthbox 3.0 must be connected to a network (with internet) to use the app.

Overview of the different screens

General dashboard

Figure 42. General dashboard

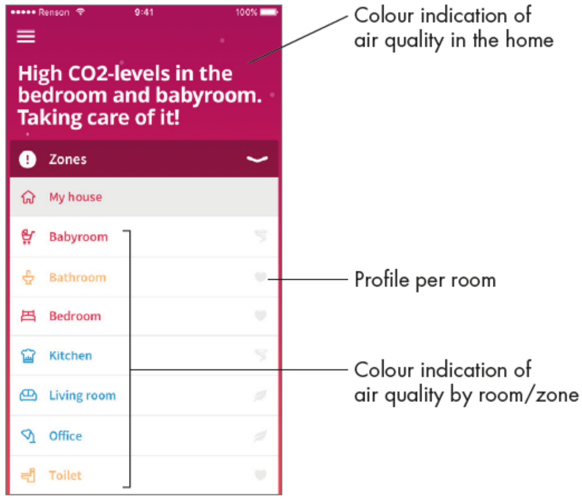


(1) If the app is connected to several Healthbox 3.0 devices.

Overview per room/zone:

The app provides a view of the air quality and the corresponding ventilation level by a clear colour indication.
Blue: good air quality
Orange: moderate air quality
Red: substandard air quality

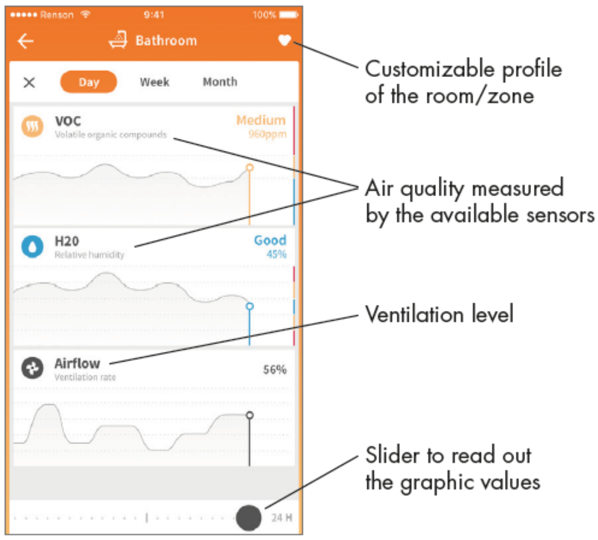
Figure 43. Overview per room/zone



History of the air quality in the room/zone (both on a daily, weekly and monthly basis)

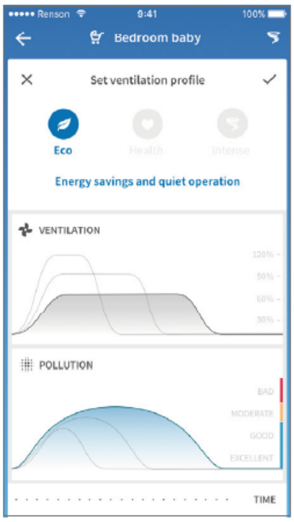
The occupant can effectively see how Healthbox 3.0 adjusts the ventilation level accordingly.

Figure 44. History



Customizable profile: the ventilation level per room/zone is fully automatically adapted to users' habits but can also be customised to suit the occupant.

Figure 45. Customizable profile

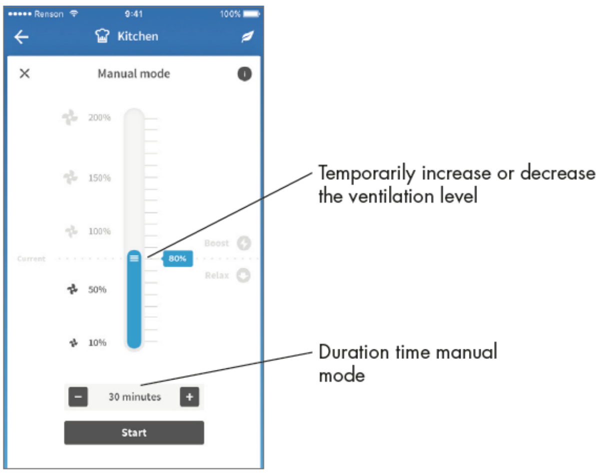


All profiles are based on demand control:

- **The Eco profile** prioritizes the energy efficient aspect where the polluted air is discharged with a lower ventilation level over a longer period of time.
- **The Health profile** ensures healthy indoor air and is energy efficient due to the demand-controlled ventilation system (normal setting).
- **The Intense profile** ensures that contaminated air is discharged more quickly via an intensified ventilation level.

Manual mode: occupants can manually set a higher or lower ventilation level for a certain duration. This can be done either per room/zone or for the entire school (if designed for). Manual mode is independent of the present sensors and overrides all other settings.

Figure 46. Manual mode



LIO WEBPORTAL

The Lio web portal, just like the app, provides the occupant additional information from the Healthbox 3.0 (provided that the device is connected to the network with internet). The web portal can be accessed via the web link www.my-lio.eu. Use the account you use for the app or register to create an account.

HEALTHBOX 3.0 IN A SMART SCHOOL

When Healthbox 3.0 is connected to the network, it offers the possibility to communicate (= data exchange) with smart devices in school management systems (automation). Connecting Healthbox 3.0 in management systems allows occupants to experience a higher overall comfort.

Control

Healthbox 3.0 is an autonomous device, but the occupant can manually adjust the ventilation level according to their wishes.

This can be done in various ways:

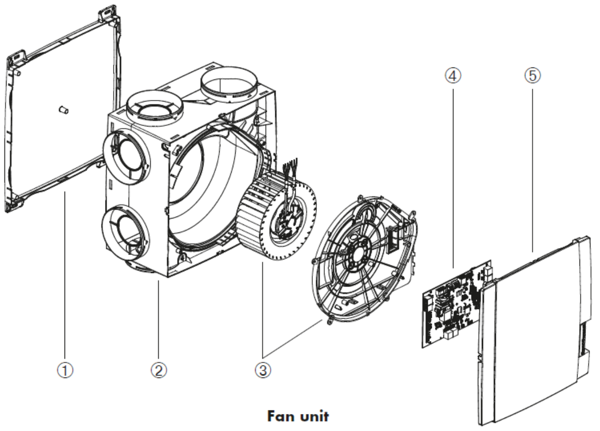
- Free app
- External switch
- Control/Control panel/app if Healthbox 3.0 is included in a smart school or school automation system

If several controls are connected to the Healthbox 3.0, then Healthbox 3.0 will assume the ventilation level / mode of the control that was last operated.

INSTALLER

Each fan unit is made up of the following parts:

Figure 47. Fan unit

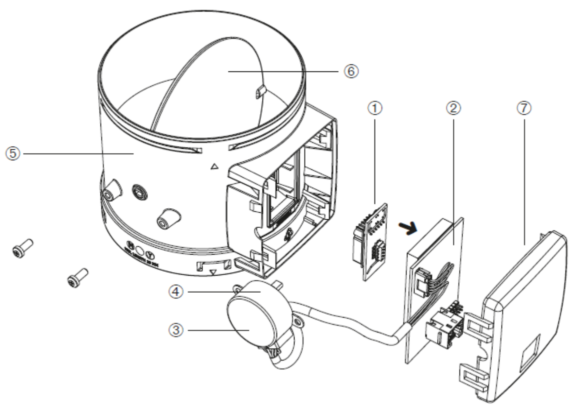


1. Mounting base
2. Pump shell
3. Assembly ventilator and motor plate
4. Main print
5. Clickable cover plate

CONTROL MODULE

The software in the Healthbox 3.0 fan unit determines how the automatic control of the ventilation level is done. That control determines how much air will be discharged per control module in function of the measured air quality and is determined by parameters such as nominal air flow, minimum air flow, limit value sensors, duration control, etc. Air quality is detected in a room/zone by means of (an) integrated sensor(s) in the control module that performs local measurements in the airflow.

Figure 48. Control module



1. Plug on print with sensor(s)
2. Circuit board (with foam)
3. Sticker with symbol
4. Stepper motor
5. Mantel control module
6. Damper blade
7. Control module cover

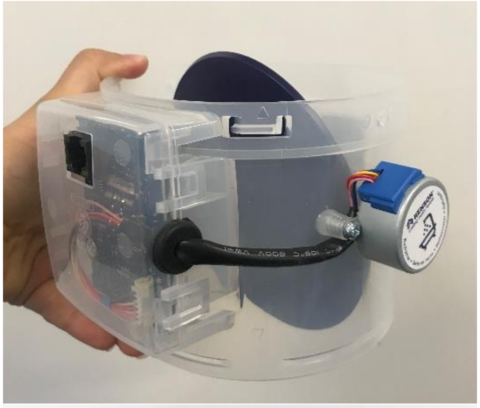
VALVE COLLECTOR

The valve collector for Healthbox 3.0 gives the installer the following advantages:

1. Increases the number of control modules that can be connected (up to max. 11)
2. Possibility to install the air duct works more compactly
3. Possibility to reduce the required air duct works

The valve collector is connected to Healthbox 3.0 via RJ45 patch cable.

HEALTHBOX® 3.0: The smart solution for healthy indoor air



Healthbox installed in A6 – placed in the ceiling.

INVISIVENT® EVO: Ventilator installed in the window which supply fresh, healthy air

Four vents in the ceiling removes polluted air

8. SUMMARY

Schools present important energy and environmental problems. In particular, schools present a much higher occupancy than any other building, accommodating four times as many occupants per unit of area than office buildings. Children spend almost 12% of their time, inside classrooms, more than in any other building environment except their home.

High indoor pollutant concentration may have a significant adverse impact on the health of students, given that children are much more vulnerable to indoor pollutants, as they breathe more air than adults relative to their weights, while their organs and tissues are growing. In parallel, non-proper indoor environmental quality influences highly the learning capacity of the students and increases absenteeism levels.

To avoid immediate health problems due to indoor air quality, normally the first action is providing proper ventilation. Adequate and proper ventilation would ideally bring enough outdoor air to help in the reduction of indoor air pollutants. This study was performed to propose, implement, monitor and evaluate the performance of proper advanced hybrid ventilation technologies able to provide the best possible indoor air quality and comfort.

To achieve the objectives this study performed detailed experimental investigations in two classrooms of a private school (St. Spyridon College) to identify the impact of indoor environmental quality on comfort. The experimental campaign was conducted from winter 2018 to Autumn/mi-season 2019. Indoor air and thermal parameters were monitored continuously with the resolution of 1-minute intervals during the monitoring period. Ventilation and infiltration rate were measured. A hybrid ventilation system was installed in January 2019 in one of the two classrooms. The system was connected to WiFi and communicated with smart devices to enable real time monitoring of the classroom air quality, temperature and humidity. The system supplies fresh and clean air and removes the polluted air from the classroom. VOCs were measured and samples of classroom air taken from two surveyed classrooms for analysis.

Analysis of indoor air quality and thermal comfort shows significant improvements in reducing CO_2 and VOCs in classroom with ventilation (A6) compared to the classroom without a ventilation system (A5). This will ultimately help to reduce adverse health impacts of the environmental condition on children and improve productivity and performance. Furthermore, it was found that Australian students feel comfortable at a neutral temperature of 23.4 °C. This is consistent with previous literature and highlights that children feel comfortable at slightly lower thermal environments compared to adults.

Further research should be proposed and implemented for a larger sample of schools. Future research is needed to determine the discrepancies between the schools, classrooms, laboratories, determine exposures in other surrounding schools which are not tested here.

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APPENDIX 1

Date: ……/04/19 Time: ……

Class: A…..

I am a: ☐Female ☐Male student, or ☐ prefer not to answer

I am: ☐12-13 years old ☐13-14 years old ☐15-16 years old ☐16-17 years old ☐17-18 years old

My body weight is about: ……(Kg)
My body height is about: …… (m)

1. <u>At the moment</u> in the classroom, do you feel:

☐Cold ☐Cool ☐Slightly cool ☐Neutral ☐Slightly warm ☐Warm ☐Hot

2. <u>At the moment,</u> do you prefer the classroom temperature to be:

☐Cooler ☐No change ☐Warmer

3. <u>At the moment</u>, do you feel the temperature in the classroom is comfortable?

☐Yes ☐No

4. <u>At the moment</u>, are you wearing jumper or jacket?

☐Yes ☐No

5. <u>At the moment</u>, do you feel tired?

☐Very sleepy and tired ☐A bit sleepy and tired ☐Not tired and sleepy

6. <u>At the moment</u>, how would you describe air movement in your classroom?

☐Still ☐Mild ☐Droughty

7. <u>At the moment</u>, do you think the indoor air quality in the classroom is acceptable?

☐Yes ☐No

8. <u>At the moment</u>, how would you characterize air quality in the classroom?

☐Very good ☐Good ☐Normal ☐Bad ☐Very bad

9. What did you do during the previous break before you came to the classroom?

☐Running ☐Walking ☐Relaxing/Sitting ☐Eating food/ drinking beverages ☐Reading/Writing

10. How do you characterise your health condition?

☐Very good ☐Good ☐Normal ☐Bad ☐Very bad

11. Are there any diseases which you suffer?

☐Yes ☐No

Please specify: …………………………………

12. Do you have any allergy?

☐Yes ☐No

Please specify: …………………………………

13. Who is responsible for adjusting the classroom temperature?

☐ School principle
☐ Teacher(s)
☐ Maintenance worker
☐ Student(s)
☐ Not sure

14. How satisfied are you with your opportunities to adjust the classroom temperature?

☐Very satisfied
☐Somewhat satisfied
☐Neither satisfied nor dissatisfied
☐Somewhat dissatisfied
☐Very dissatisfied

15. Which of the following do you personally adjust or control in the classroom?

Check all that apply.

☐ Window (s)
☐ Blind (s)
☐ Door
☐ Air-conditioning system
☐ Ceiling Fan
☐ None of these
☐ Other (please specify): --

16. If you adjust any of the above in this classroom, what is the main reason for using them?

☐ Because I feel hot or cold during the lesson (shivering, sweating, or complaining)
☐ Because my teacher or classmates feel hot or cold during the lesson
☐ Because classroom gets stuffy and needs fresh air (for windows and doors only)
☐ Other (please specify): --

17. If you open/close the window in this classroom, how often do you do it?

☐ Never
☐ Rarely
☐ Sometimes when needed
☐ Often
☐ Always

18. If you control the air-conditioning system in the classroom, how often do you do it?

☐ Never
☐ Rarely
☐ Sometimes when it is needed
☐ Often
☐ Always

19. If you don't use any of the above (window, door, blind, or air-condition system), what are the main reasons?

Tick more than one if appropriate

For windows and doors

☐ Outdoor noise
☐ Security
☐ May notebook/papers fly-around
☐ Limited access to the window(s) openings
☐ No need
☐ Other (please specify) ---

For air conditioning

☐ Limited access to the thermostat
☐ No need
☐ Other (please specify) ---

For blind(s)

☐ Distraction caused by visual access to outside
☐ Limited access to the blind(s)
☐ No need
☐ Other (please specify) ---

20. How long does thermal discomfort last when it occurs in the classroom?

Please estimate to the nearest hour: --

21. When does the classroom get cold or hot?

My classroom gets *cold* mainly in the:

☐ Morning
☐ Midday
☐ Afternoon
☐ No particular time
☐ Other (please specify): ---

My classroom gets *hot* mainly in the:

☐ Morning
☐ Midday
☐ Afternoon
☐ No particular time
☐ Other (please specify): ---

22. When the classroom gets cold or hot, what do you operate first?

☐ Close/open the window
☐ Close/open the door
☐ Pull up/down the blinds
☐ Turn on/off the air-conditioning
☐ Turn on/off the ceiling fan
☐ Wear/ remove a jacket and ask the students to do so
☐ Other (please specify): ---

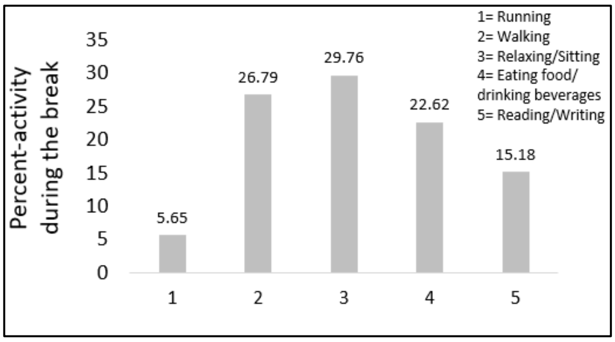
23. How do you evaluate the overall quality of your classroom?

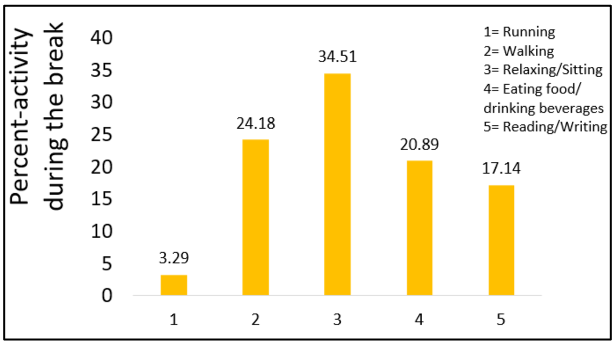
☐Very good ☐Good ☐Average ☐Bad ☐Very bad

APPENDIX 2

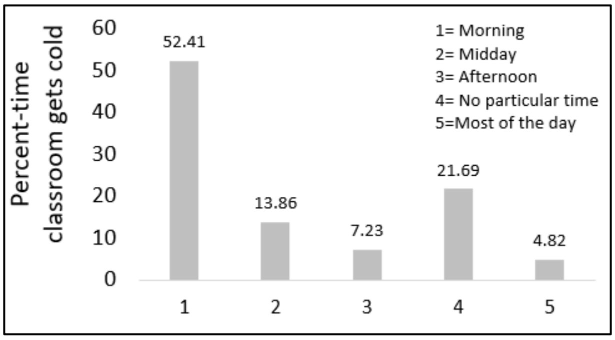
Bar graphs presented here show the percentage of responses to the questions given below for winter and mid-season respectively.

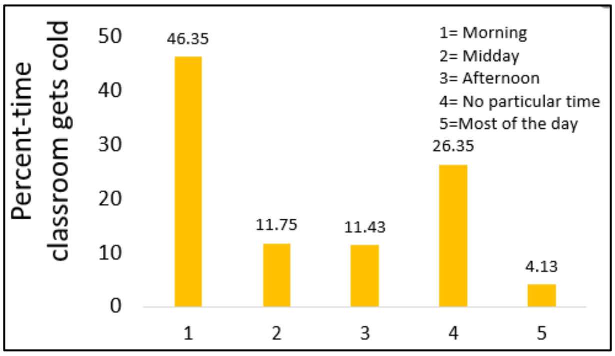
What did you do during the previous break before you came to the classroom?



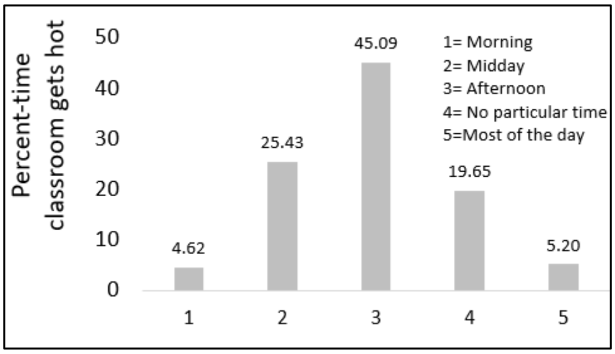


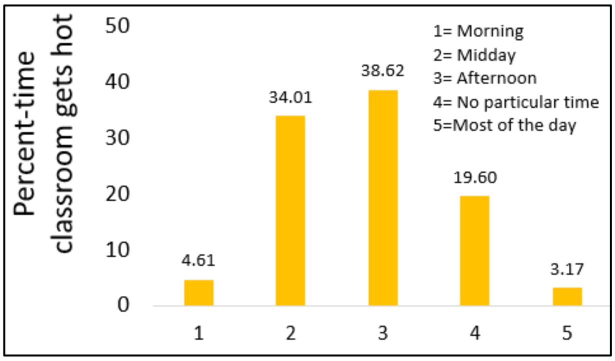
My classroom gets cold mainly in the:



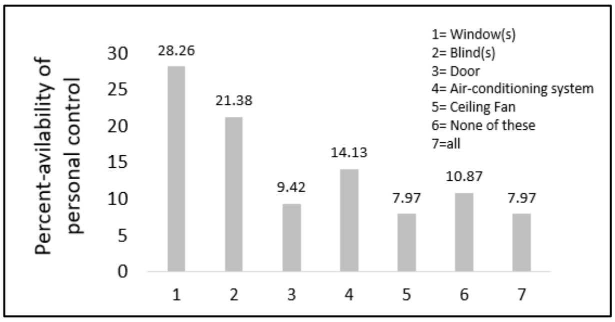


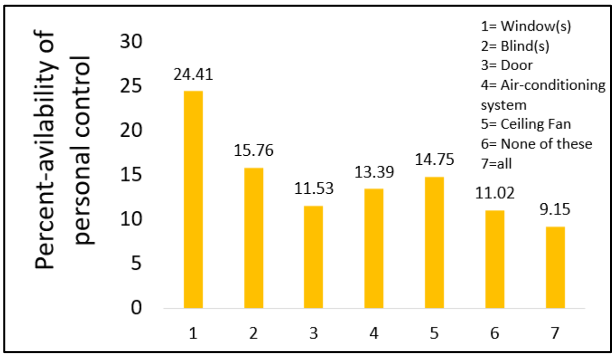
My classroom gets hot mainly in the:



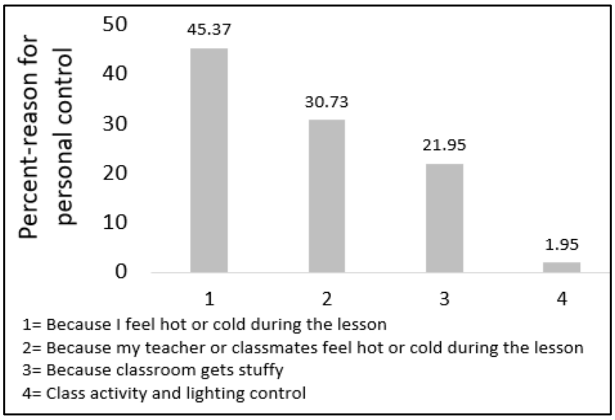


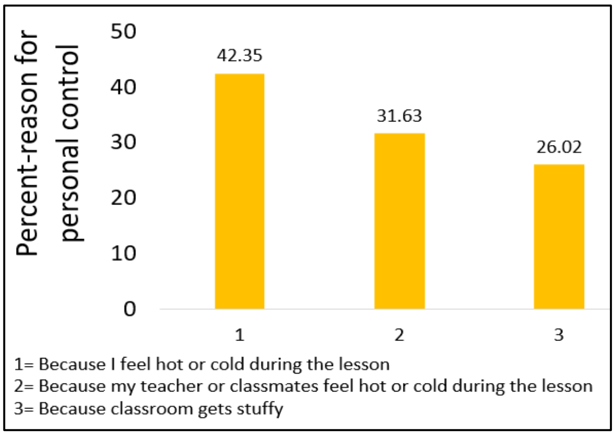
Which of the following do you personally adjust or control in the classroom?



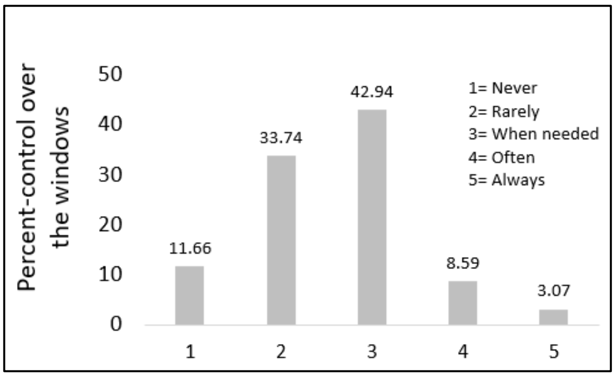


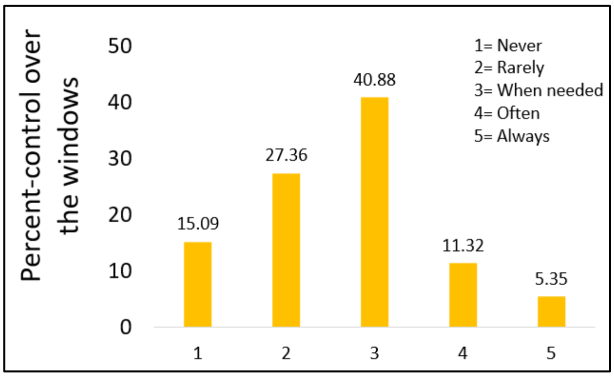
If you adjust any of the above in this classroom, what is the main reason for using them?



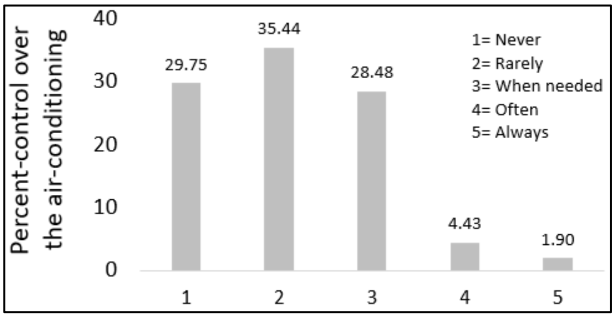


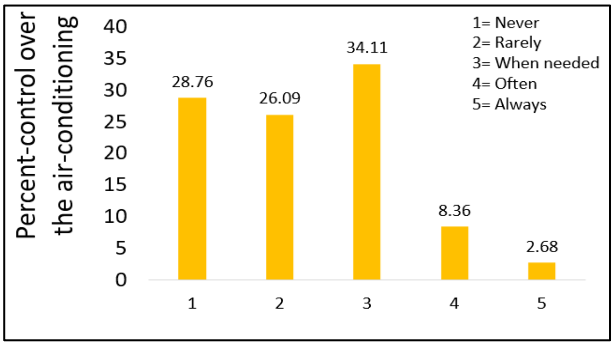
If you open/close the window in this classroom, how often do you do it?



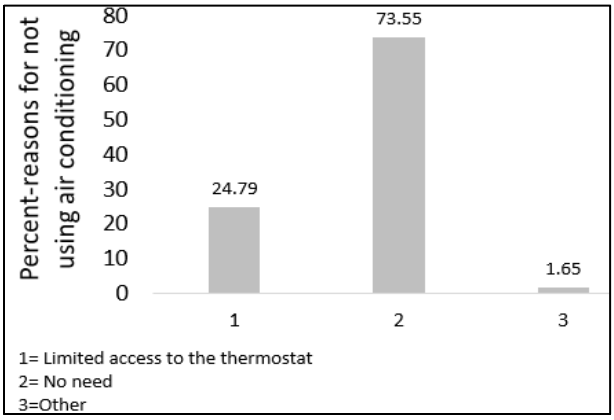


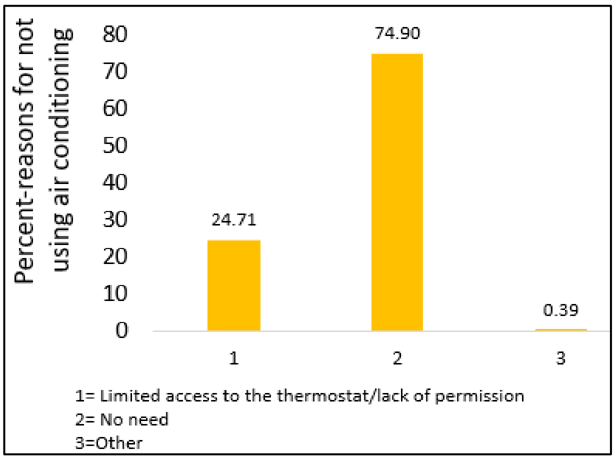
If you control the air-conditioning system in the classroom, how often do you do it?



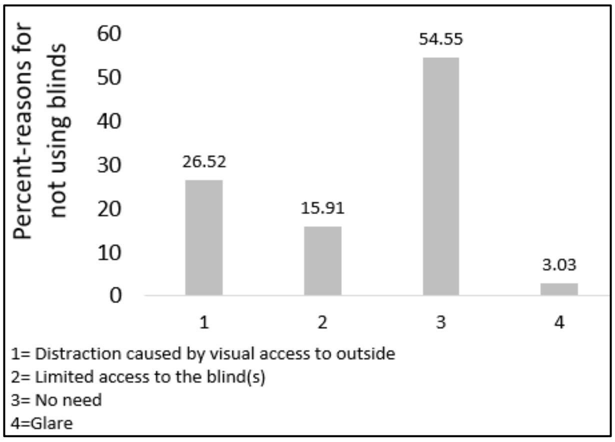


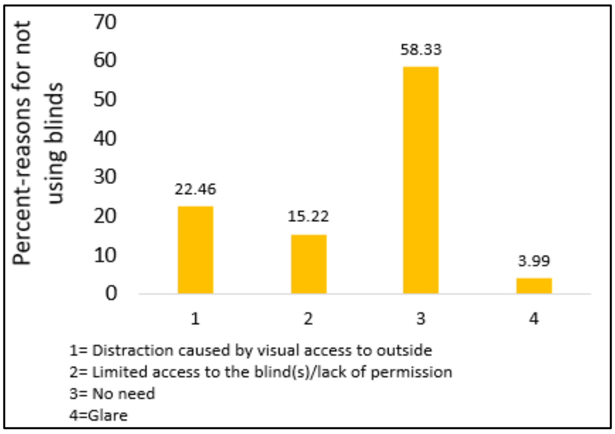
If you don't use air-condition system what are the main reasons?



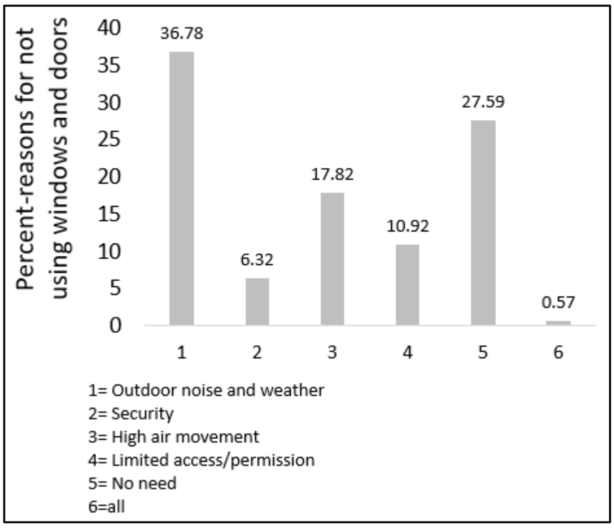


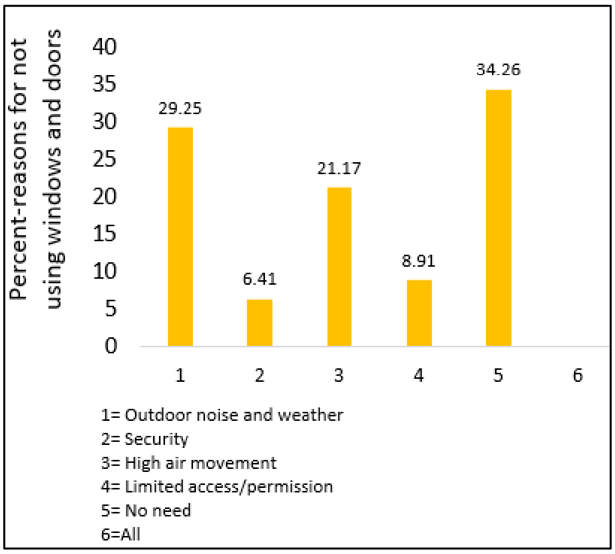
If you don't use blind what are the main reasons?





If you don't use window and door what are the main reasons?





When the classroom gets cold or hot, what do you operate first?