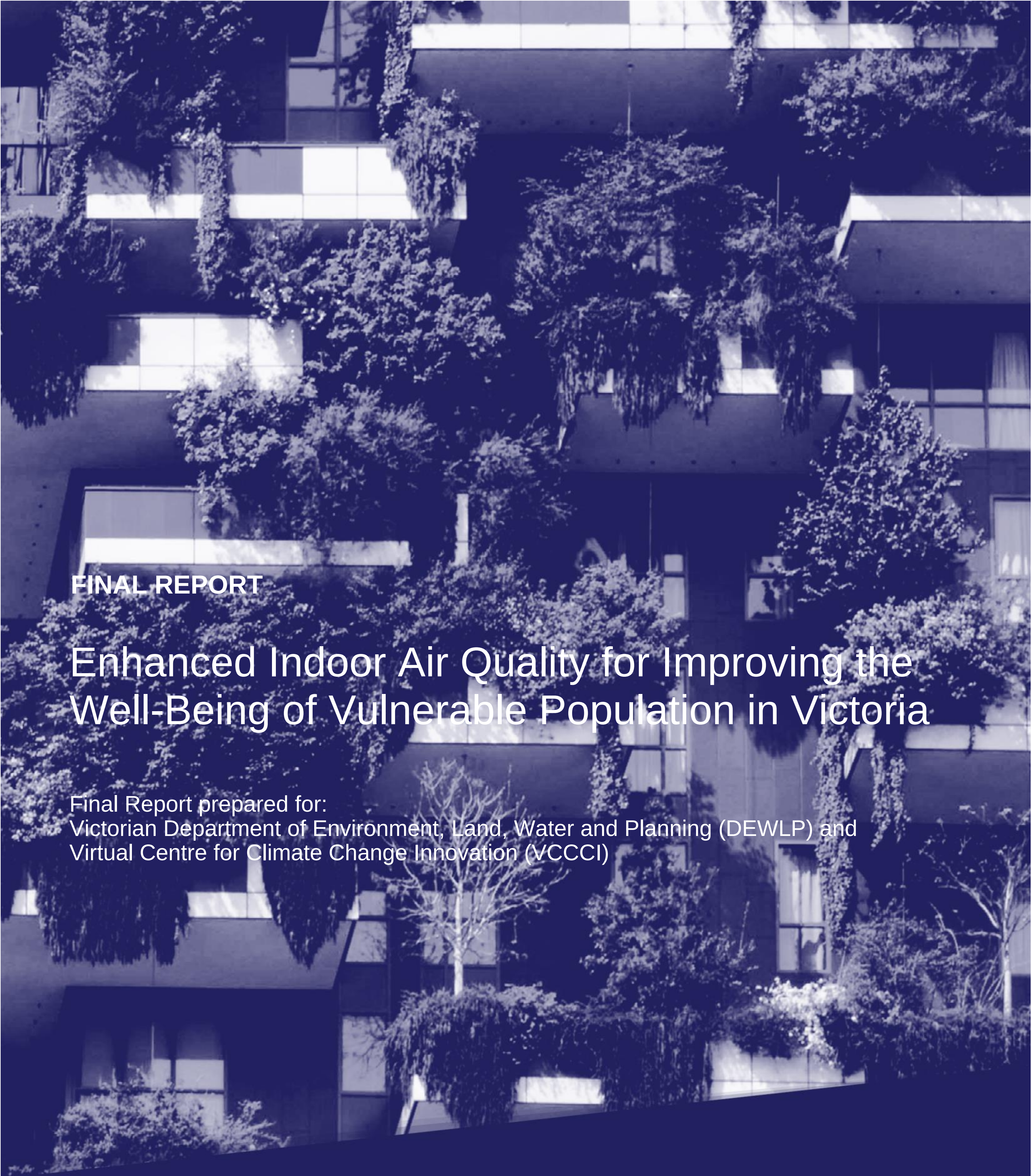

FINAL REPORT

Enhanced Indoor Air Quality for Improving the Well-Being of Vulnerable Population in Victoria

Final Report prepared for:
Victorian Department of Environment, Land, Water and Planning (DEWLP) and
Virtual Centre for Climate Change Innovation (VCCCI)

RMIT UNIVERSITY

Sustainable Building Innovation Laboratory

School of Property, Construction and Project Management

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Part 1: Executive Summary

Climate change has deteriorated the air quality of cities leading to increased temperature, increased level of carbon dioxide and other pollutants such as dust and allergens. Extreme weather events such as heat waves, thunderstorms and bushfire smoke are rising. Increasing frequency of such extreme weather events will force people to spend even more time indoor. Several studies demonstrate the importance of indoor air quality on health, well-being and productivity of occupants. However, much of the research on indoor environments focuses on adult workers in offices while a significant proportion of Australia's population consist of young children in schools and old people in aged care homes who are vulnerable to worsening indoor air quality. Also, there is limited information on the relationship between indoor environment and health and well-being of the elderly as well as the learning performance and educational outcomes of school children.

This study investigated indoor air quality (IAQ) in schools and aged care homes using one-year long monitoring and measurements. The monitoring provided a comprehensive understanding of the actual conditions of the selected schools and aged care homes in different settings and an overview of the various physical and operational factors affecting IAQ in these facilities. The average CO_2 concentration levels in the different school classrooms ranged from 912 to 2235 ppm, while the maximum concentration levels reached up to 5000 ppm during certain times of the occupied hours. The air change rates (ACH) ranged between 0.68 to 4.28 and were below the recommended standards in seven out of the ten classrooms investigated. Level of particulate matter (PM) were within the guidelines stipulated by the World Health Organization. In the aged care home common rooms, CO_2 concentration levels reached up to 2000 ppm. The ACH ranged from 0.84 to 3.81 and ventilation rates ranged from 5.52 Ls^{-1} per person to 30.95 Ls^{-1} per person.

The impact of IAQ parameters on students' attention and concentration was examined using the d2 Test of Attention (d2 Attention test) - a performance test that measures concentration, selective attention and speeded visual perceptual discrimination. The results of d2 Attention tests established a low to moderate correlation between ventilation rates and student performance across the four school terms, particularly speed and accuracy, demonstrating that IAQ does impact student concentration performance. Stepwise multiple regression analysis showed that 16.1% of the variance in speed and accuracy is explained by the four indoor condition parameters of $PM_{2.5}$, mean radiant temperature, relative humidity and air velocity. Other factors such as lighting and noise levels, health and socio-economic conditions of individual students may also have influenced the test results. These should be further explored with the use of a questionnaire survey.

This study also explored the benefits of adding a fresh filtered air ventilation system in the selected spaces. The fresh filtered air ventilation system was installed independent of the existing heating, ventilation and air conditioning (HVAC) system in each of the facilities. The results of the monitoring showed that the addition of fresh filtered air ventilation system reduced the indoor CO_2 concentration levels by as much as 1000ppm. However, in contrast, no reduction was observed in the PM concentration levels. In fact, the PM concentration levels were found to be very much influenced by the local activities and movement of people inside the room and particularly by the opening and closing of windows and doors in the case of school classrooms. Identification of specific sources of particles would require further control experiments targeting various activities.

The main contributions of the study are:

- The study is grounded on addressing the lack of clear documentation on the state of indoor environments in Australian schools and aged care facilities and backed by long-term monitoring and measurements in actual operating conditions.
- This study provided information on the state of IAQ in selected school classrooms and in the common rooms in aged care homes. The findings also presented an overview of how various designs and operating conditions in school classrooms and aged care homes located in different geographic locations affect ventilation rates and indoor air quality in various seasons.
- The study also provided insights about the interdisciplinary aspects of IAQ in school classrooms which were not previously explored in Australian conditions; and demonstrated a method for analysing the effect of IAQ on students' learning performance.
- The findings could be used to inform guidelines on building construction, envelope airtightness, heating and cooling policy and ventilation standards. The findings can also inform the operation and maintenance of classrooms and HVAC systems including filter grade and fresh air intake.

Part 2: Project

2.1 Background

Indoor air quality (IAQ) directly impacts occupant health, comfort and work performance. Breathing conditioned but re-circulated air continuously without adequate fresh air can cause poor concentration of mind, lung diseases and mental disorder. Various health symptoms due to poor air quality include eye, nose and throat irritation; mental fatigue; headache; cough; difficulty in breathing and concentrating. The problem is going to get worse as climate change has been worsening the air quality of cities leading to increased temperature, level of carbon dioxide concentration and other pollutants such as dust and allergens. Much of the research on indoor environments focuses on adult workers in offices and there is limited information on the relationship between indoor environment, well-being of elderly and the learning performance and behaviour of young children. In Australia, people aged 65 years and older make up a significant proportion. Several studies in other countries have found that elderly is susceptible to potential indoor pollutants even at low concentrations. However, scientific studies on IAQ related impacts on the health of aged care home residents in Australia are limited. Similarly, Children under 15 years constitute approximately 19% of the Australian population (ABS, 2019) and are particularly vulnerable to poor air quality (WHO, 2018). These young students spend over six hours per day or up to 12,900 hours of their waking lives in school buildings, yet little is known about the IAQ conditions in classrooms and how it affects their well-being and educational outcomes. For children, lung development continues through childhood and lung function grows at least through adolescence. Chemical exposure during developmental stages may produce lifelong issues, and some may become apparent only later in life (WHO, 2018). Therefore, the conditions of indoor environmental quality in school buildings and their impact on children’s health, well-being, comfort and learning ability remains a subject area of concern.

This project “*Enhanced Indoor Air Quality for Improving the Well-being of Vulnerable Population in Victoria*” investigates the IAQ conditions in school classrooms and aged care homes and also aims to enhance the IAQ in these facilities through the application of fresh filtered air ventilation system. The study outcomes are intended to develop new evidence aimed at improving the well-being and educational outcomes of young children and quality of life and resilience of older Australians, assisting in climate change adaptation. The study is grounded on addressing the lack of clear documentation on the state of indoor environments in Australian aged care and school facilities backed by measurements and investigation of the relationship between aspects of indoor environments, air quality and student performance. The core activity of this project is the long-term monitoring, assessment and evaluation of the indoor air quality of five (5) aged care homes and five (5) schools in Victoria during various seasons before and after installing a fresh filtered air ventilation system.

2.2 Stakeholders

Eco Pacific Pty Ltd – industry partner

Regis Aged Care

Vasey RSL Care

Multicultural Aged Care Services, Geelong

Victoria School Building Authority – endorsement of the participation of three (3) public primary schools and one (1) secondary school. A private primary school also participated in the project.

2.3 Project Approval

Human Research Ethics Approval

Following RMIT University's requirement for ethics approval for any research conducted with or about people, the ethics application outlining the adequacy of the project's research design and compliance with recognised ethical standards was lodged with the College Human Ethics Advisory Network (CHEAN). The ethics application was approved on 20 July 2018 (expiry 30 June 2020) with Project Number CHEAN B 21563-06/18 with a 'low risk' classification. Refer to Part 9: Appendices for the ethics approval issued by RMIT University – Design and Social Context College Office.

Victorian Department of Education and Training (DET)

The schools intended to be monitored for the project are public primary schools. In conducting research in Victorian government schools, the Victorian School Building Authority (VSBA) required the approval of the research by the Victorian Department of Education and Training (DET). The application was lodged on 29 June 2018. With the ethics approval from RMIT University, DET approved the research project on 17 August 2018 with Project Number 2018_00371. Refer to Part 9: Appendices

Part 3: Indoor Air Quality (IAQ) and Ventilation

3.1 Criteria for IAQ and Ventilation

The criteria and recommendations in the international standards have been adopted as normative references by Australian national standards, guidelines and codes of practice. Unlike the specifications for thermal environments, it has not been possible to agree on a method for specifying the level of indoor air quality in buildings. Instead, required ventilation rates are specified for different types of space and occupancy (Olesen, 2004). ANSI/ASHRAE Standard 62.1: *Ventilation for Acceptable Indoor Air Quality* (ASHRAE, 2019a) presents methods of achieving acceptable indoor air quality which is defined as safe contaminant concentrations and a high level of occupant satisfaction in the context of non-residential buildings. ASHRAE 62.2: *Ventilation for Acceptable Indoor Air Quality in Residential Buildings* (ASHRAE, 2019b) presents minimum requirements for mechanical and natural ventilation systems to provide acceptable indoor air quality in residential buildings. The requirements of the standard include not only ventilation rate but also outdoor air, construction process, moisture and biological growth (Khovalyg et al., 2020). Standards Australia sets out design requirements for ventilation based on different types of ventilation systems. AS 1668.2 *The use of ventilation and air conditioning in buildings - Part 2: Mechanical ventilation in buildings*, provides permissible ventilation rates to achieve acceptable indoor air quality. The standard includes guidelines on mechanical ventilation supply and exhaust systems, the ventilation of enclosures used by vehicles with combustion engines and the mechanical ventilation of enclosures used for health care functions (Standards Australia, 2012a). AS 1668.4 *The use of ventilation and air conditioning in buildings - Part 4: Natural ventilation of buildings*, sets out minimum design requirements for natural ventilation systems, however, does not prescribe any requirements related to comfort (Standards Australia, 2012b). These standards and guides prescribe minimum ventilation rates as a means of achieving acceptable indoor air quality (Francisco, 2011). The following standards were associated with the present research.

Schools

All standards address both the health and comfort issue. These standards include a prescriptive method, where the minimum ventilation rates can be found in a table listing values for different type of space, as well as an analytical procedure for calculation of the required ventilation rate (Olesen, 2004). By using the analytical procedure, the ventilation rates can be calculated on the basis of the type of pollutant, emission rates and acceptable concentration

ASHRAE Standard 62.1 classified air quality according to the levels of contamination. CR 1752: V*entilation for buildings - Design criteria for the indoor environment* (CEN, 1998) expressed the categories of air quality according to the percentage of dissatisfied: the values given for the three classes correspond to A – 15% dissatisfied, B – 20% dissatisfied and C – 30% dissatisfied.

The number of indoor air quality indicators with different corresponding criterion on concentration and exposure levels makes it challenging to calculate the quality of indoor air based on emission rates from materials and other sources. Furthermore, there is a lack of information on emission rates of pollutants in select building categories and exposure levels of certain sectors of population. In place of calculating the concentration levels and exposure to pollutants and contaminants as well as carrying out actual monitoring, using the prescribed ventilation rates is viewed to adequately address the achievement of the required indoor air quality for a space or building.

For naturally ventilated school buildings, Class 9b buildings as classified by National Construction Code - Building Code of Australia (ABCB, 2019), AS 1668.4 (Standards Australia, 2012b) specifies that natural ventilation shall be provided to an enclosure by direct ventilation openings that have an area not less than 5% of the floor area of the enclosure. For borrowed ventilation, the internal opening shall have an area of not less than 10% of the floor area of the room to be ventilated, measured not more than 3.6m above the floor and the adjoining room shall have an external opening with a ventilating area of not less than 10% of the combined floor area of both rooms. AS 1668.4 also provides an alternative detailed procedure where the percentage floor area required as openings for classrooms is calculated by the floor area requirement per occupant and multiplied by a factor of 1.25.

The basis of criteria for IAQ and ventilation rates is the general acceptance that IAQ is influenced by emission from people and their activities, from building and furnishing, and from the HVAC system itself (DIN, 2007). Indoor carbon dioxide (CO_2) concentration measurements are commonly used as indicators of indoor ventilation and surrogates for IAQ. When concentration levels exceed 1,000 ppm, insufficient ventilation and unacceptable conditions in relation to odours removal is indicated (ASTM, 2018). Outdoor carbon dioxide (CO_2) concentration levels typically range between 300 to 500 ppm, and typical indoor CO_2 concentration levels range between 500 to 1,500 ppm (Seppänen, 2006). ASHRAE Standard 62.1 recommends a steady-state CO_2 concentration in a space no greater than about 700 ppm above outdoor air levels with ventilation rate to be held to 5 Ls^{-1} per person for classrooms (age 9 plus). AS 1668.2 specifies a minimum floor area requirement per occupant and recommends minimum outdoor airflow rate between 10-12 Ls^{-1} per person. For example, minimum floor area of $2m^2$ per person in classrooms and 12 Ls^{-1} per person serving persons up to 16 years of age. However, there is no information on minimum CO_2 concentrations or other indoor air pollutants exposure levels. NZS 4303: *Ventilation for acceptable indoor air quality* (Standards New Zealand, 1990) specifies 8 Ls^{-1} per person as fresh air requirement in a class of 30 students, and adopts the benchmark of 1,000 ppm CO_2 concentration levels.

Aged care homes

AS 1668.2 specifies a minimum floor area requirement per occupant and recommends minimum outdoor airflow rate for health care facilities including convalescent homes and nursing homes. However, special requirements determine minimum ventilation rates and filter efficiency (e.g. operating theatres and intensive care rooms). For patient rooms which can be referenced for aged care homes, the minimum outdoor air flow rate is 10-12 Ls^{-1} per person with a net floor area of $10m^2$ per person.

ASHRAE Standard 62.1 does not prescribe ventilation rates specifically for aged care homes but recommend a range of ventilation rates for outpatient healthcare facilities ranging from 2.5 Ls^{-1} for examination and consultation rooms, 5 Ls^{-1} for physical therapy individual rooms and 10 Ls^{-1} for physical therapy exercise area. However, ASHRAE Standard 170: *Ventilation of Health Care Facilities* (ASHRAE, 2017b) prescribes 2 ACH for resident rooms and 4 ACH for resident gathering/activity/dining spaces with MERV 13 filter efficiency requirement (equivalent to F6-F7 Australian Standard performance rating).

EN 15251: *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics* (DIN, 2007) outlines a Category I recommendation for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick or elderly persons and prescribes the airflow rate of 10 Ls^{-1} per person or 1.4 Ls^{-1}/m^2 for living room and bedrooms, mainly outdoor air flow and for continuous operation of ventilation during occupied hours (complete mixing) (DIN, 2007, Table B.5, p37).

3.2 Factors affecting IAQ – Ventilation and their Measurements

Acceptable IAQ can be achieved by appropriate ventilation mode and rate but IAQ might degrade when ventilation processes are inadequate. Ventilation refers to a combination of processes that results in the supply and removal of air from inside a building. These processes include bringing in outdoor air, conditioning and mixing the outdoor air with some portion of indoor air, distributing this mixed air throughout the building, and exhausting some portion of the indoor air outside either through mechanical ventilation systems or by infiltration through building envelope with the help of natural forces such as wind pressure and air temperature difference between indoor and outdoor air (Seppänen et al., 1999; US EPA, 1993). The following are considered as affective IAQ factors and are investigated in this study.

Thermal Environments

The perception of air quality can be strongly influenced by temperature and humidity. Studies show that perceived indoor air was less acceptable according to the increase in indoor air temperature and/or humidity even when the chemical composition of the air was constant, and the thermal sensation was kept neutral. By contrast, when the air is cool and dry, the perceived air is fresh and acceptable (Fang et al., 1998; Fang et al., 2004; Simonson et al., 2002; Tham, 2004). It clearly shows high temperature and humidity counteract increased ventilation rate, and thus degrade perceived indoor air quality.

CO_2 Concentration Levels

Carbon dioxide (CO_2) can be used as an indicator for the indoor pollutants and ventilation rate per occupant. CO_2 produced by occupants' breathing could increase indoors if there is an insufficient amount of outdoor air brought into and distributed throughout the building. A steady-state indoor CO_2 concentration level of 1000 ppm has been used as an informal threshold between adequate and inadequate ventilation. Higher concentrations have been associated with increased frequency of health symptoms and increased absence in office workers (Milton et al., 2000). On the other hand, the risk of SBS symptoms continue to decrease significantly with decreasing CO_2 concentrations below 800 ppm (Seppänen et al., 1999). The CO_2 build-up is thought to be a surrogate for occupant-generated pollutants and ventilation rate per occupant, but not a causal factor in human health responses (Apte et al., 2000).

Particulate Matter

Particulate matter (PM) is used as a proxy indicator of air pollution broadly and is recognised as one of the pollutants of public health concern by World Health Organizations (WHO). Numerous previous studies conducted worldwide have assessed that the indoor PM levels are generally higher than outdoor levels. The United States Environmental Protection Agency (2018) indicates that indoor pollutant levels maybe two to five times - and occasionally more than 100 times higher than outdoor levels. Indoor particulate matter concentration is a function of several factors even in the absence of any significant indoor sources of particles. The most important of these factors are the outdoor particle concentration, air exchange rate, particle penetration efficiency from the outdoor to the indoor environment, the particle deposition rate on indoor surfaces, and outdoor meteorological factors. $PM_{2.5}$ consists of particles of any substances that are less than 2.5 micrometres in diameter. $PM_{2.5}$ is generally described as fine particles, the common sources of which are smoke from fires, cooking and vehicle exhausts. PM_{10} consists of particles of any substances that are less than 10 micrometres. The presence of people is a major source of PM_{10} indoors.

Pathogens

Microorganisms are ubiquitous in the indoor and outdoor environment. Microbes such as bacteria and mould propagate rapidly wherever water is available. The dust and dirt normally present in most spaces provide sufficient nutrients to support extensive microbial growth. The prevention of dampness is one of the most critical factors in controlling microbial growth in indoor environments. It is important to note that there are no regulatory standards or health-based standards or guidelines for surface and airborne microbial pollutants. Even though most sampling methods do not distinguish between fungi species and comparison between indoor and outdoor levels is problematic, the indoor/outdoor relationship can be used as an indicator of a possible difference between the two environments. For mechanically ventilated buildings, when the indoor fungi count is more than half (>0.5) of the outdoor fungi count, there could be potential elevated health risks (Kemp and Neumeister, 2010, p9), and health symptoms should be noted.

3.3 IAQ and Human Performance

It has been evident that indoor air quality (IAQ) can negatively affect the health of building occupants by increasing the prevalence of general symptoms (Berglund et al., 1992; Mendell, M.J., 2003; Molhave et al., 1986). Human body can automatically operate controls to reach a state of health, yet people often feel unwell for no apparent reason when they are in a building. The symptoms can be explained in terms of the sick building syndrome (SBS), which is ‘a situation in a building where more people than normal suffer from various symptoms or feel unwell for no apparent reason’ (Appleby, 1996, p. 674).

Although there is consensus that poor IAQ may impact children's health there has not been a clear relationship found between them in schools. Annesi-Maesano et al. (2013) argued that data from scientific literature indicated that poor air quality may influence school children's respiratory health and academic performance, however, it seems that other adverse health effects are less documented.

Student Performance

Indoor air quality (IAQ) can influence student performance in schools. A review on the factors that influence student performance reported that 'persuasive' evidence linked higher indoor concentrations of NO_2 to reduced school attendance and 'suggestive' evidence linked low ventilation rates to reduced performance (Mendell, M. J. and Heath, 2005). More recent research found a reduction in concentration performance when students were exposed to high CO_2 concentration levels although the results did not reach statistical significance. With reference to an experimental cross-over study in six classrooms, the authors cited that a significantly reduced student concentration was observed at low air quality with CO_2 concentration levels of at least 3000 ppm (Twardella et al., 2012). Not surprisingly, most research measured student performance in a controlled environment, using simulated tasks such as addition, text typing and neurobehavioural tests (Geng et al., 2017; Jiang et al., 2018) in order to establish a cause-effect relation. The simulated tasks are to measure student performance quantitatively, and two of the performance indicators are reaction time and accuracy.

Health and Well-Being of the Elderly

The elderly can be highly affected by indoor air quality as they are likely to stay longer indoors. Maio et al. (2015) analysed recent literature on air quality and its health effect on the elderly in nursing homes and ascertained that elderly residents are at risk of respiratory health impairment at moderate air pollution concentrations, particularly if they are over 80 years old and living in poorly ventilated buildings. They can be potentially more exposed to indoor air pollutions including PM_{10}, $PM_{2.5}$, $PM_{0.1}$, ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOCs), allergens and microorganisms (Bentayeb et al., 2013; Maio et al., 2015). In a review study, Lee et al. (2007) investigated an association between particulate matter and the peak expiratory flow rate (PEFR) among the elderly, and compared estimated risks using PM_{10} or $PM_{2.5}$ levels as a measure of exposure. During a two-year longitudinal study, the authors demonstrated a significant negative relationship between air particle level and PEFR, showing a stronger association with $PM_{2.5}$ than with PM_{10}. It implicates that smaller particles are likely to have a more adverse respiratory health impact on sensitive individuals such as the elderly.

Part 4: Methodology and Approach

4.1 Participating schools

Four primary schools (S1, S2, S3, S4) and one secondary school (S5) participated in the study. Except for School S1 located in regional Victoria (85 km from Melbourne), all schools are located in Melbourne area at distances of 3, 7, 13 and 17 km from the central business district (Figure 1). School S1 is in a residential suburban area south of Geelong CBD. School S2 is in a residential suburban area southeast of Melbourne CBD next to a busy thoroughfare and a bus stop. School S3 is in an inner-city residential area east of Melbourne CBD. Similar to School S2, School S4 is located in residential suburban area northwest of Melbourne CBD but next to a minor residential road. School S5 is in a residential suburban area north of Melbourne CBD.

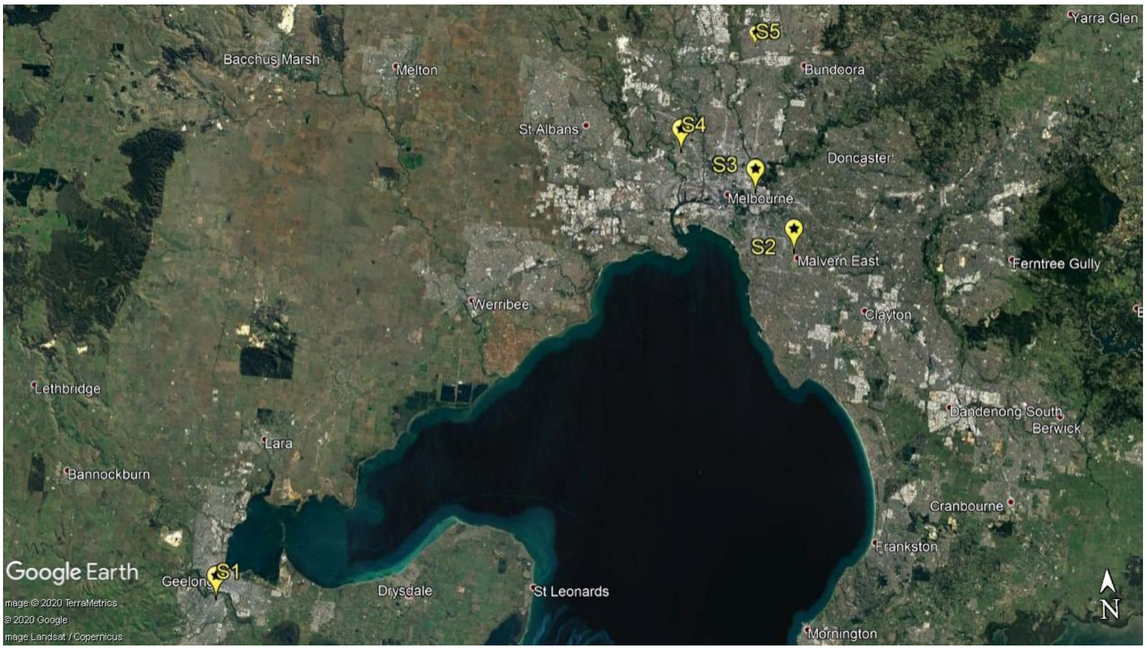

Figure 1 Locations of schools

4.2 Research approach for school classrooms

Ten classrooms in the five schools (Classrooms A and B from Schools S1 to S5) were selected for the study. Two (2) classrooms from each of the five (5) schools were monitored and assessed for one academic year (4 school terms) from February to December 2019. For the duration of the one-year experiment, the indoor environmental conditions (air temperature, relative humidity, carbon dioxide (CO_2) concentration levels) were continuously monitored with stationary battery-operated datalogger (HOBO MX1102). Particulate matter was also monitored for a week during four school terms representing summer, autumn, winter and spring seasons using Aerocet handheld particle counter Model 531S. In addition, microbial (bacteria and mould) concentration levels were measured, one sample each, before and after the installation of the supplementary ventilation system (Section 4.5). The microbial sampling involved the collection of one air sample from each facility using a sampling pump at a flow rate of 28 Lm^{-1} for two minutes to estimate the total count of microbials before and after the installation of the ventilation system in Classrooms B (intervention rooms). Figure 2 shows the typical monitoring instrumentation and sensors set-up in the classroom. Specifications of the instruments and sensors are available in Part 8: Supplementary Information, Table S1.

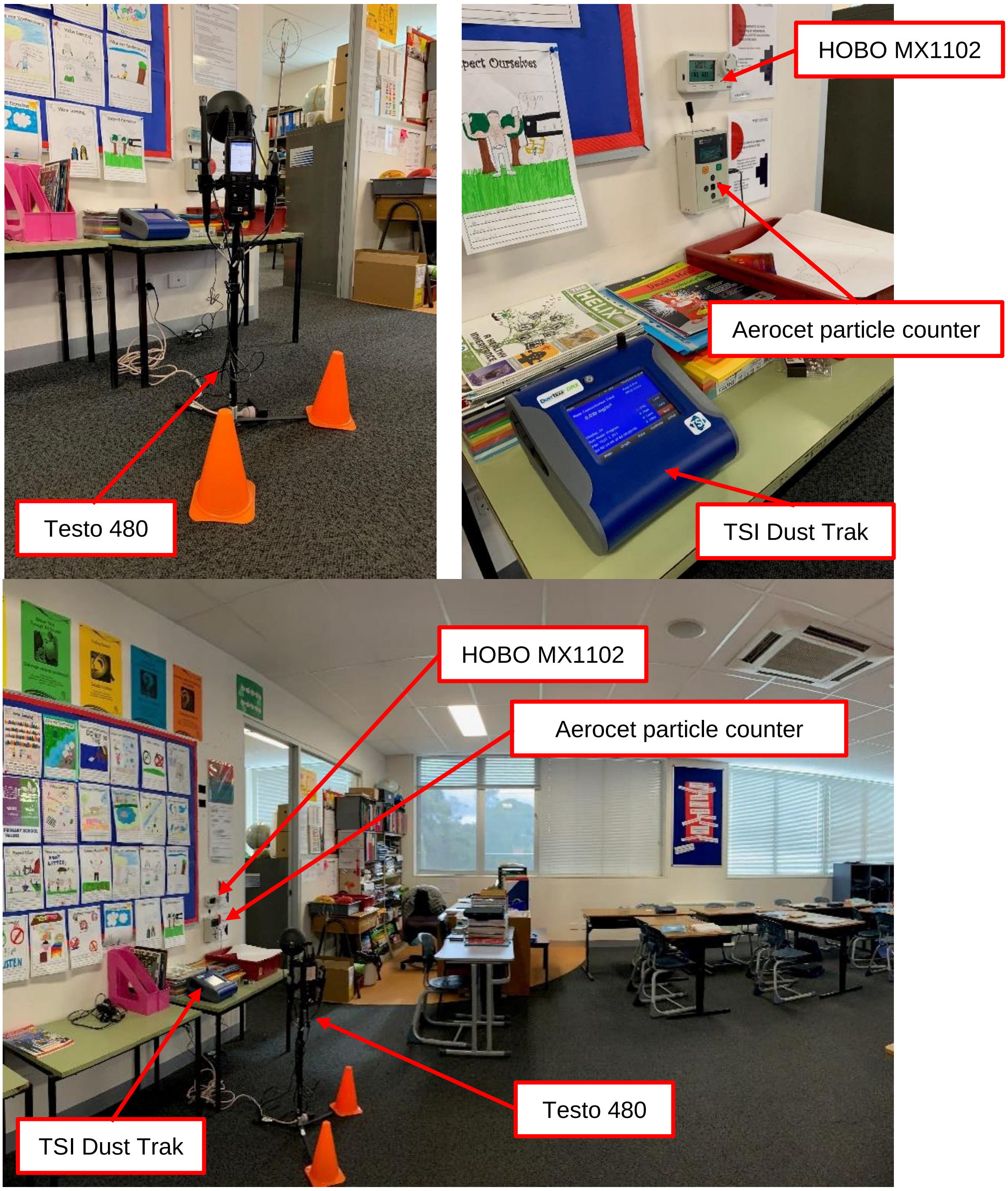

Figure 2 Typical monitoring instrumentation set-up in classrooms

To measure student performance, d2 Attention test was used. The d2 Attention test was performed in the ten classrooms for one day per school term during four terms. During these survey and test days, on-the-spot (day-long) measurements of the indoor environmental conditions (air temperature, globe temperature, relative humidity, CO_2 concentration levels and air velocity) were conducted using a portable IEQ datalogger, Testo 480. These day-long measurements taken from the centre of the classroom, without obstructing student activities, were cross-referenced with those logged by the stationary instrumentation (HOBO dataloggers). The relationship between IAQ parameters and student concentration performance was analysed using statistical methods.

Classrooms B (intervention rooms) were fitted with a supplementary fresh filtered air ventilation system described in Section 4.5 just before academic Term 3 commenced. The ventilation system supplied supplementary fresh filtered air with G4 filter grade. For Schools S2, S3, S4 and S5, the G4 pre-filters were supplemented with F7 filters and added booster fans post Term 4 (December 2019). Classrooms A were simultaneously monitored as the base case rooms for comparison.

4.3 Participating aged care homes

Five aged care homes (AC1, AC2, AC3, AC4, AC5) participated in the study. Except for AC5 located in regional Victoria (85 km from Melbourne), all aged care homes are located in Melbourne area at distances of 43, 23, 16 and 12 km from the central business district (Figure 3). AC1 to AC4 are located in residential suburban areas whereas AC5 is located just outside the residential area in the north of Geelong. AC1 is located 43 km south east of Melbourne CBD. AC2 and AC3, respectively are located 23 km and 16 km east of Melbourne CBD. AC4 is located 12 km southeast of Melbourne CBD.

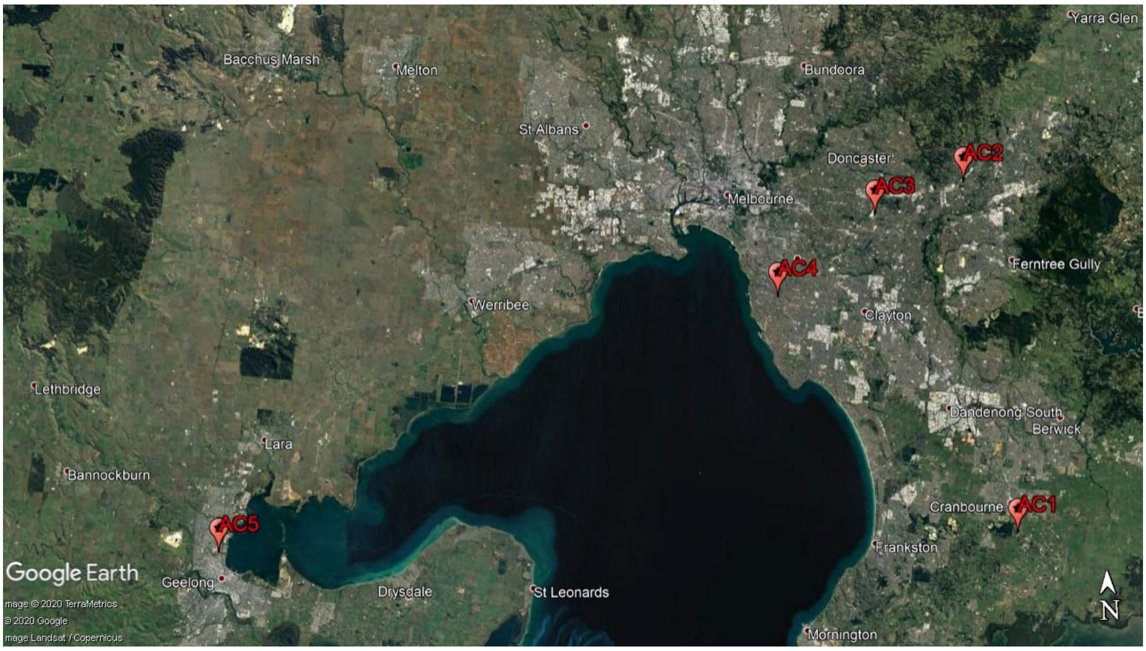

Figure 3 Locations of aged care homes

4.4 Research approach for aged care homes

Ten common rooms in five aged care homes (Rooms A and B from aged care homes AC1-AC5) were selected for the study. The supplementary ventilation system was installed in one of the rooms for each facility whilst the other room was monitored as a base case for comparison. IAQ parameters were measured for a duration of 14 months from January 2019-Februay 2020. For the duration of the one-year experiment, the indoor environmental conditions (air temperature, relative humidity, carbon dioxide (CO_2) concentration levels) were continuously monitored with stationary battery-operated datalogger (HOBO MX1102). Particulate matter is also monitored for a week during four seasons using Aerocet handheld particle counter Model 531S. Microbial (bacteria and mould) concentration levels were also measured. Similar to the school classrooms, the microbial sampling involved the collection of one air sample from each facility using a sampling pump at a flow rate of 28 Lm^{-1} for two minutes to estimate the total count of microbials before and after the installation of the ventilation system in Common Rooms B (intervention rooms). Figure 4 shows the typical monitoring instrumentation and sensors set-up in the aged care homes. Specifications of the instruments and sensors are available in Part 8: Supplementary Information, Table S1.

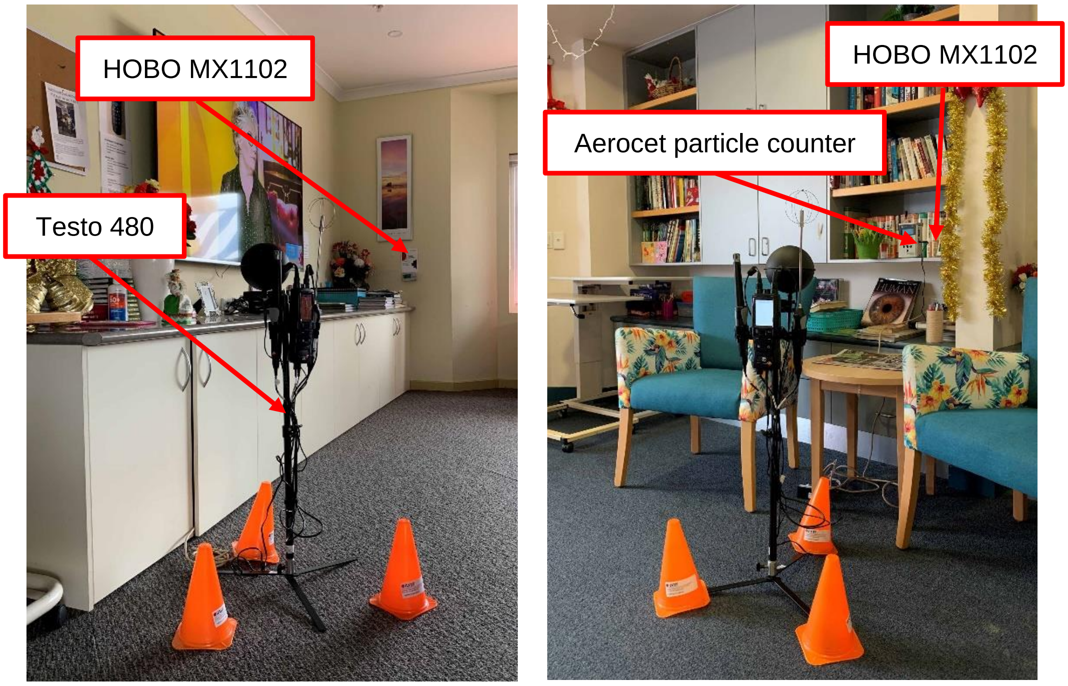

Figure 4 Typical monitoring instrumentation set-up in aged care homes

Common Rooms B (intervention rooms) in aged care homes were fitted with supplementary fresh filtered air ventilation system described in Section 4.5 in September-November 2019. The ventilation system supplied supplementary fresh filtered air with G4 filter grade. For aged care homes AC1, AC2 and AC3, the G4 pre-filters were supplemented with F7 filter and added booster fans in January 2020.

4.5 Supplementary ventilation system

The Fresh Filtered Air Heat Recovery Ventilation system (FAHRV) in this project, developed by the industry partner Eco Pacific is shown in Figure 5a. The system is made of a metal box fitted with two small DC brushless motors on each side of the heat exchanger which is mounted in the middle of the cabinet. The motors are controlled by a digital display wall controller (Figure 5b) equipped with CO_2 and $PM_{2.5}$ sensors. The filter box (Figure 5c) is fitted with a standard G4 pre-filter. For further filtration, additional filters such as F7 can be fitted in the same filter box.

Figure 5 (a) Heat recovery ventilation (b) Wall controller (c) Air filter box (Source: Eco Pacific)

The system is simple, light weight, and easy to open and close for service in narrow-constricted roof spaces. The specification of the system is as below:

- Dimensions – 800 mm (L) x 556 mm (W) x 187 mm (D);
- Duct connections – 150 mm barbed suitable for 150 mm grille vents fitted in the ceiling for supply and return air;
- 240V, 50Hz, air flow 80 l/s at ESP of 90 Pa,
- HR Efficiency 86%, noise 30dB, weight 20 kg

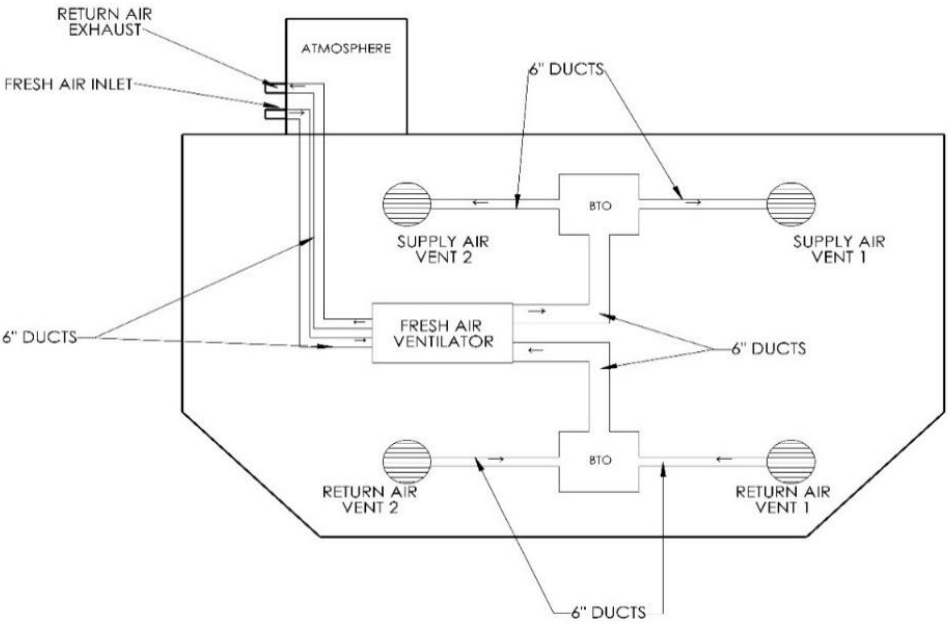

Figure 6 Typical installation (plan) layout of the supplementary ventilation system (Source: Eco Pacific)

The HRV cabinet is mounted in the roof space, if adequate crawling space is available, or on top of the roof if flat metal roof is accessible. The wall controller goes indoor on the inner wall, and the fresh air filter box goes either on top of the roof, under the eve, or on the outer wall to capture and filter fresh air. The system, once installed, recovers heat/coolth from the indoor stale exhaust air at the heat exchanger and transfers it into the incoming (outdoor) fresh air. A typical installation (plan) layout is shown in Figure 6 with two points each for return air and supply air vents in the ceiling cavity. Table 1 shows the supply air velocity and airflow rates measured at the supply point (supply grilles) for each of the school classrooms and aged care homes.

Figure 7 (1) Roof installation, (2) Ceiling installation, (3) External filter box installation (Source: Eco Pacific)

Table 1 Air flow rates as measured at supply point (Source: Eco Pacific)

Facility	Original (G4 pre-filter)		Upgrade (plus (F7 filter)	
	Supply air velocity (ms^{-1})	Supply air flow rate (m^3/h)	Supply air velocity (ms^{-1})	Supply air flow rate (m^3/h)
S1B	1.2	142.56		
S2B	0.9	106.92	2.9	344.52
S3B	1.4	166.32	3.4	403.92
S4B	1.3	154.44	3.3	392.04
S5B	1.4	166.32	3.4	403.92
AC1B	1.8	213.84	2.8	332.64
AC2B	1.6	190.08	3.3	392.04
AC3B	2.1	249.48	3.1	368.28
AC4B	1.5	178.20		
AC5B	1.9	225.72		

After 12 months of monitoring, an additional F7 filter was added in the filter box to supplement the G4 pre-filter. Low noise fans capable to withstand higher pressure drops with the addition of F7 filters was installed to increase airflow rates. Duct connectors were used to fit the boosters in line at the suction of the return air and discharge of the supply air. Classroom S1B system was not upgraded due to insufficient ceiling space for the booster fan. Upgrades to Rooms AC4B and AC5B were not approved due to the addition of booster fans. The increased airflow rates for the rooms with upgrades system are as shown in Table 1.

4.6 Description of schools

The five (5) school buildings were built in the last 10-20 years and all ten (10) classrooms are provided with mechanical air conditioning systems. The building structure and construction are typical of the school building stock in terms of age, typology and construction specification. The classroom sizes range from a floor area of 55-81m^2 and volume of 160-210m^3 with occupancy of 15-27 students. Table 2 shows the physical properties including area, volume, construction details and type of ventilation systems in each of the classrooms. Interior images of the school classrooms are shown in Figure 8 to Figure 17.

Table 2 School classrooms characteristics

School	Classroom	A (m^2)	CH (m)	V (m^3)	Construction	Ventilation
S1	S1A	75.5	2.3-3.3	202.4	Ground floor location; standalone building; metal cladding walls with insulation; perforated metal ceiling; east and west windows; loop pile carpet tile floors	Relocatable classroom, Openable windows – west rear windows are always kept close (windowpanes are covered with student work); east front windows and doors were at times kept open; split air conditioning system; ceiling fans
	S1B	75.5	2.3-3.3	202.4	Ground floor location; standalone building; metal cladding walls with insulation; perforated metal ceiling; east and west windows; loop pile carpet tile floors	
S2	S2A	81.0	2.6	210.6	First level location; fibre cement cladding walls; clear single glazed north-east windows with micro-venetian blinds; loop pile carpet tile floors	Openable windows – windows closed in S2A and mostly open in S2B, doors open in S2A and S2B; cassette type (ceiling mounted) split air conditioning – reverse cycle; supplementary floor mounted electric convection heater.
	S2B	81.0	2.6	210.6	First level location; fibre cement cladding walls; clear single glazed north-east windows with micro-venetian blinds; loop pile carpet tile floors	
S3	S3A	58.7	3.0	176.2	First level location, brick veneer walls; clear single glazed north windows; loop pile carpet tile floors	Openable windows – windows and doors closed in S3A, windows and door open in S3B; cassette type

School	Classroom	A (m^2)	CH (m)	V (m^3)	Construction	Ventilation
	S3B	54.9	3.0	164.7	First level location, brick veneer; clear single glazed south windows; loop pile carpet tile floors	(ceiling mounted) split air conditioning – reverse cycle; supplementary floor mounted electric convection heater; ceiling fans
S4	S4A	80.0	2.7	216.0	First level location, brick veneer walls; clear single glazed south windows; loop pile carpet floor finish	Openable windows – windows closed, doors sometimes open to the corridor in S4A and S4B; cassette type (ceiling mounted) split air conditioning – reverse cycle
	S4B	81.3	2.7	219.5	First level location, fibre cement cladding walls; clear single glazed north windows; loop pile carpet floor finish	
S5	S5A	61.7	2.9	178.0	Ground floor location; brick veneer walls; no windows; loop pile carpet floor finish	Classrooms not provided with windows, south facing doors are often open to external corridor; cassette type (ceiling mounted) split air conditioning – reverse cycle; ceiling fans
	S5B	63.0	3.10	195.4	Ground floor location; brick veneer walls; no windows; loop pile carpet floor finish	

Figure 8 Classroom S1A

Figure 9 Classroom S1B

Figure 10 Classroom S2A

Figure 11 Classroom S2B

Figure 12 Classroom S3A

Figure 13 Classroom S3B

Figure 14 Classroom S4A

Figure 15 Classroom S4B

Figure 16 Classroom S5A

Figure 17 Classroom S5B

4.7 Description of aged care homes

The research involved five aged care homes located in Victoria. Four of them were in the suburbs of Melbourne and one in a suburb of Geelong. All buildings were low-rise and most of the buildings had exterior brick walls. A total of ten common rooms, two rooms per aged care home, were selected to evaluate the ventilation system. The rooms were selected based on the frequency of use and ease of installation.

Table 3 shows the physical properties including area, volume, construction details and type of ventilation systems in each of the common rooms. The floor area ranged from 57.8 m^2 to 165 m^2 per room with an average of 121.1 m^2 and the ceiling height were between 2.4 m and 5.3 m. Interior walls were painted on plaster or gypsum board lining and internal floor finishes were mainly carpet and wood or vinyl flooring in kitchenette and dining area where waterproof/water resistant flooring were needed. Most of the rooms were sufficiently daylit with internal shading such as roll screens and curtains. Over half of the rooms had central air conditioning (AC) units installed, two had reverse cycle AC and the other two had cassette units. It is noted that some rooms had additional electric heaters used during winter. The number of occupants varied from unoccupied to 33 people in accordance with events and activities held in the aged care homes. Interior images of the aged care homes are shown in Figure 18 to Figure 27.

Table 3 Aged care homes characteristics

Aged care home	Room	A (m^2)	CH (m)	V (m^3)	Construction	Ventilation
AC1	AC1A	48.4	3.19	154	Ground level location; brick walls; tinted glazed windows with internal blinds; vinyl flooring	Reverse cycle AC; ceiling fans; panel heaters
	AC1B	66.4	2.5	169	Ground level location; brick walls; tinted glazed windows with awning; vinyl flooring	Central AC
AC2	AC2A	165.0	2.5-5.3	616	Ground level location; timber walls; tinted glazed windows with internal blinds and external louvres; vinyl flooring	Central AC; electric heater
	AC2B	99.5	2.7	269	Ground level location; fibre cement cladding walls; tinted glazed windows with internal blinds and external louvres; laminated timber flooring	Cassette units; electric heater
AC3	AC3A	121	3.0	363	Ground level location; brick walls; glazed windows with curtains; vinyl flooring	Central AC; panel heater
	AC3B	141	2.5	355	Ground level location; brick walls; tinted glazed windows with curtains; carpet flooring	Cassette units; reverse cycle AC
AC4	AC4A	181	3	543	Ground level location; brick/weatherboard walls; tinted glazed windows with curtains; carpet/wood flooring	Central AC; heating fan

Aged care home	Room	A (m^2)	CH (m)	V (m^3)	Construction	Ventilation
	AC4B	192	3	576	First level location; brick/weatherboard walls; clear glazed windows with internal shading; carpet/wood flooring	Central AC; heating fan
AC5	AC5A	158.7	2.7	428.5	Ground level location; brick walls; clear glazed windows; carpet flooring	Central AC
	AC5B	96.3	2.7	260.0	Ground level location; brick walls; tinted glazed windows; carpet flooring	Central AC

Figure 18 Aged care AC1A

Figure 19 Aged care AC1B

Figure 20 Aged care AC2A

Figure 21 Aged care AC2B

Figure 22 Aged care AC3A

Figure 23 Aged care AC3B

Figure 24 Aged care AC4A

Figure 25 Aged care AC4B

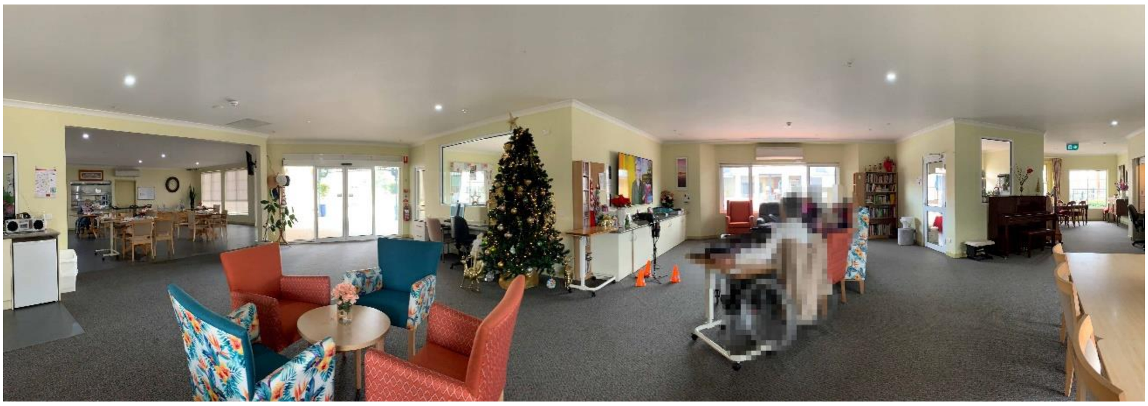

Figure 26 Aged care AC5A

Figure 27 Aged care AC5B

Part 5: Results – Schools

5.1 Indoor Conditions

Thermal Environments

Term 1 monitoring period was from February to April (summer and early autumn period) and the mean outdoor temperature range from 9.4°C to 37°C, 18-84 RH% (BoM, 2019) (Part 8: Supplementary Information, Table S2). Term 2 is from April to June which corresponds to autumn-winter period where typically the average outdoor conditions would range from 4.5°C to 23°C, 38-100 RH%. Term 3 extends from July to September representing the winter-spring season. The mean outdoor temperatures in these periods ranged from 6.4°C to 25.5°C, 42-98 RH%. The final Term 4 covers spring and early summer seasons with outdoor temperatures of 10°C to 41.3°C and relative humidity range of 13-98RH%.

The indoor air temperature and relative humidity of the ten classrooms during school hours (from 9:00am-3:30pm) across the four school terms are shown in Figure 28 and Figure 29. In Term 1, the average indoor air temperatures, were generally consistent across the ten classrooms ranging from 21.8°C to 23.8°C (std dev = 1.7-2.99) with average relative humidity levels of 50-55 RH% (std dev = 6.12-9.83). Lower average temperatures were measured in Terms 2 and 3, 18.9°C to 21.0°C (std dev = 2.09-3.38) and 18.7°C to 21.1°C (std dev = 0.99-2.87), respectively, with corresponding humidity levels of 50-63 RH% (std dev = 4.43-8.29). Term 4 indoor conditions were similar to Term 1 with average indoor temperature range of 20.1°C to 22.3°C (std dev = 1.54-2.93) and 48-56 RH% (std dev = 4.35-7.97). Details of the indoor air quality parameters measurements in the school classrooms during the monitoring period are presented in Part 8: Supplementary Information, Table S3.

The indoor air temperature and relative humidity profiles (Figure 28 and Figure 29) show that the middle 50% of measured conditions for both indoor air temperatures and relative humidity levels are consistent across the four school terms in the ten monitored classrooms. Both mean and median measures are closely aligned. These indicate that the conditions in the monitored classrooms have been mechanically controlled revolving around indoor air temperatures of 18°C - 24°C and humidity levels of 44-63 RH%. These conditions generally align with the recommended indoor air temperature and relative humidity recommended by (ASHRAE, 2017a; CIBSE, 2006; ISO, 2005).

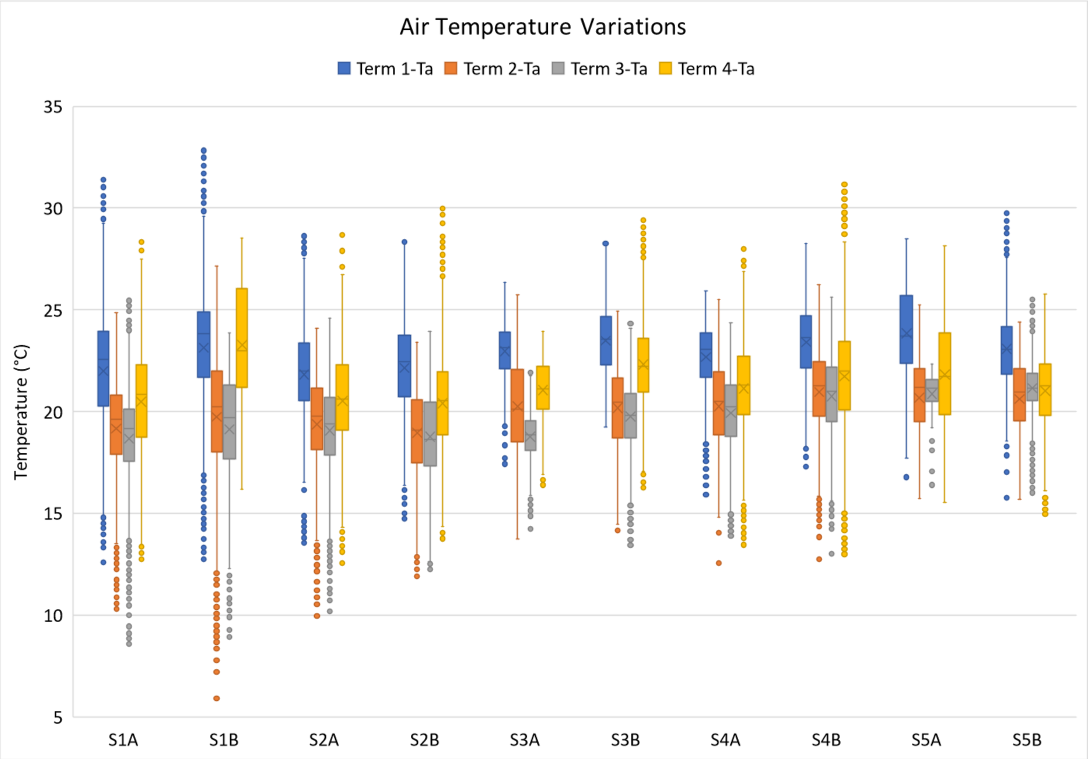

Figure 28 Air temperature (°C) variations across four (4) school terms during school hours (9:00am-3:30pm)

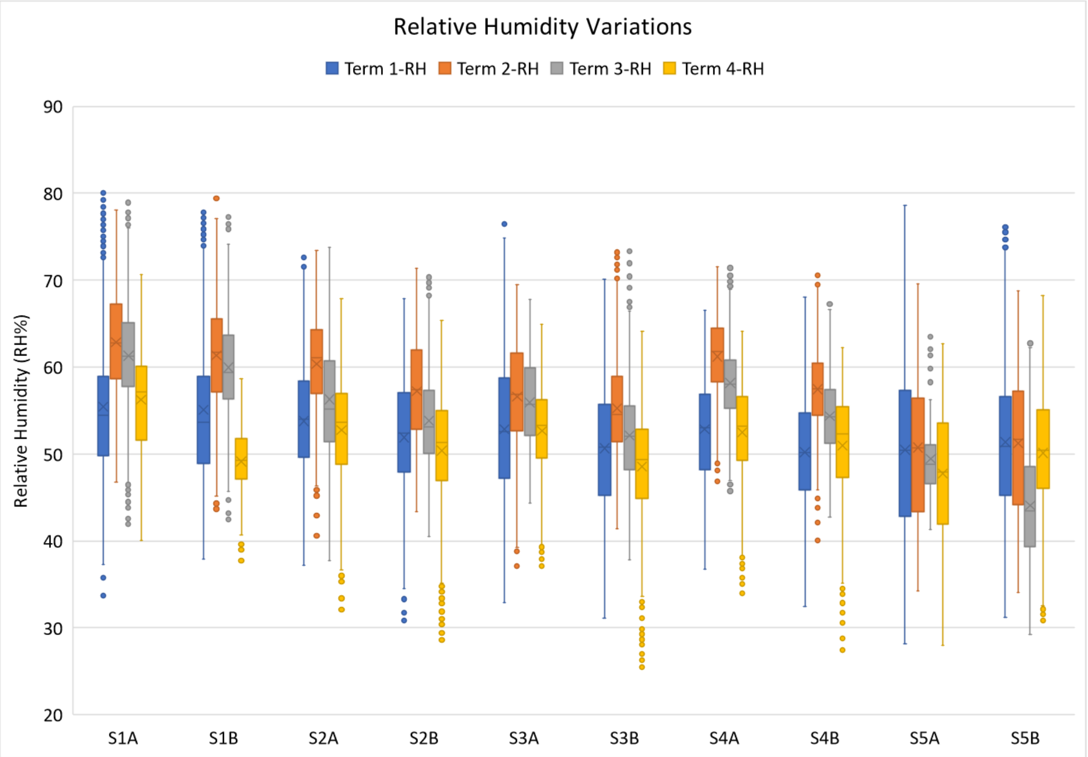

Figure 29 Relative humidity (RH%) variations across four (4) school terms during school hours (9:00am-3:30pm)

CO_2 Concentration Levels

The CO_2 concentration levels in the ten classrooms across the four school terms are shown in Figure 30 with mean values ranging from 657 ppm (std dev = 347.4) in classroom S5B to 2235 ppm (std dev = 915.2) in classroom S4A. The average CO_2 concentration levels varied significantly between the five schools with both classrooms in Schools S5 and S3 showing the lowest levels, 657 ppm-1019 ppm (std dev = 347.4-454.6) in S5B and 671 ppm - 980 ppm (std dev = 377.4-467.2) in S5A, 925 ppm - 977 ppm (std dev = 286.1-308.3) in S3B and 912 ppm - 1179 ppm (std dev = 320.9-331.9) in S3A, and similarly in S2B with 882 ppm - 1247 ppm (std dev = 403.5-502.1). Details of the CO_2 concentration levels measurements in the school classrooms during the monitoring period are presented in Part 8: Supplementary Information, Table S3.

Both classrooms in School S4 showed the highest average CO_2 concentration levels ranging from 1519 ppm to 2235 ppm (std dev = 637.3-1029.2). However, all ten classrooms showed maximum levels of CO_2 concentrations over 1700 ppm during school hours. The highest maximum CO_2 concentration levels were recorded in both S4 classrooms ranging from 3415 ppm - 5000 ppm across the four school terms. Both School S1 classrooms also showed high maximum levels ranging from 3033 ppm - 4216 ppm during the four school terms.

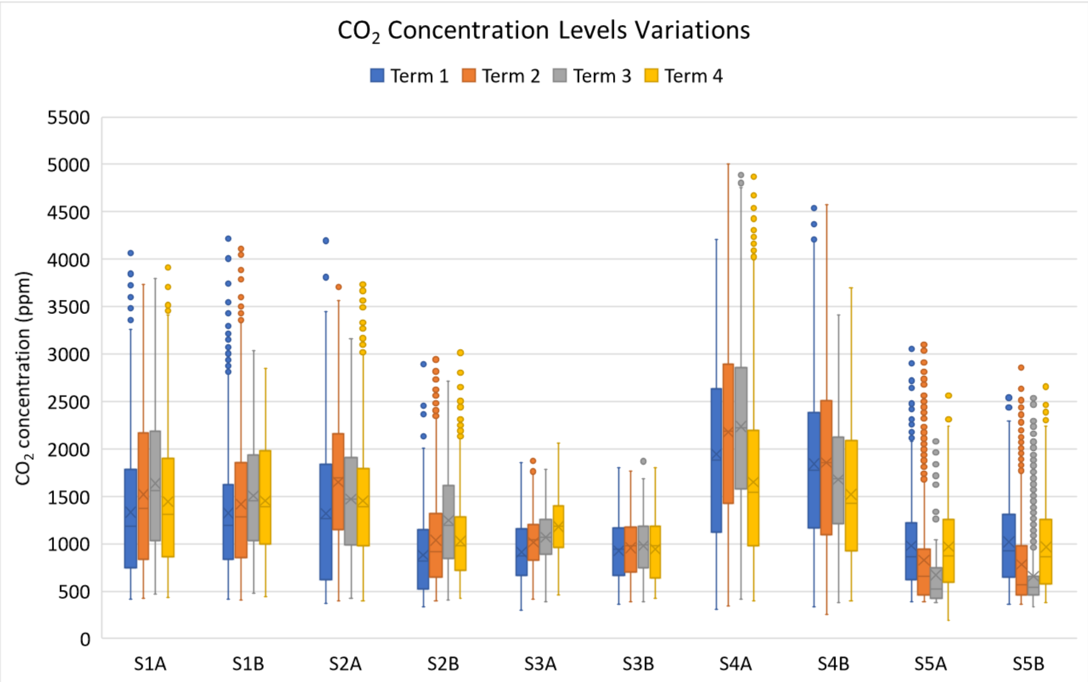

Figure 30 CO_2 concentration levels variations across four (4) school terms

The concentration levels start building up from 9:00 am as the class begins and the highest levels were found during mid-day, just before the lunch break. Another peak was also observed around 3.30 pm just before the school ends. These peak levels of CO_2 concentration are typical across the five schools. Figure 31 shows the hourly CO_2 concentration levels averaged for each term for classroom S4A (with highest CO_2 concentration levels amongst the 10 classrooms). Based on the reported classroom occupancy and teacher records, operation of air conditioning systems, opening of windows as well leaving doors wide open may have contributed the fluctuations and peak levels of the indoor CO_2 concentration levels (Figure 30).

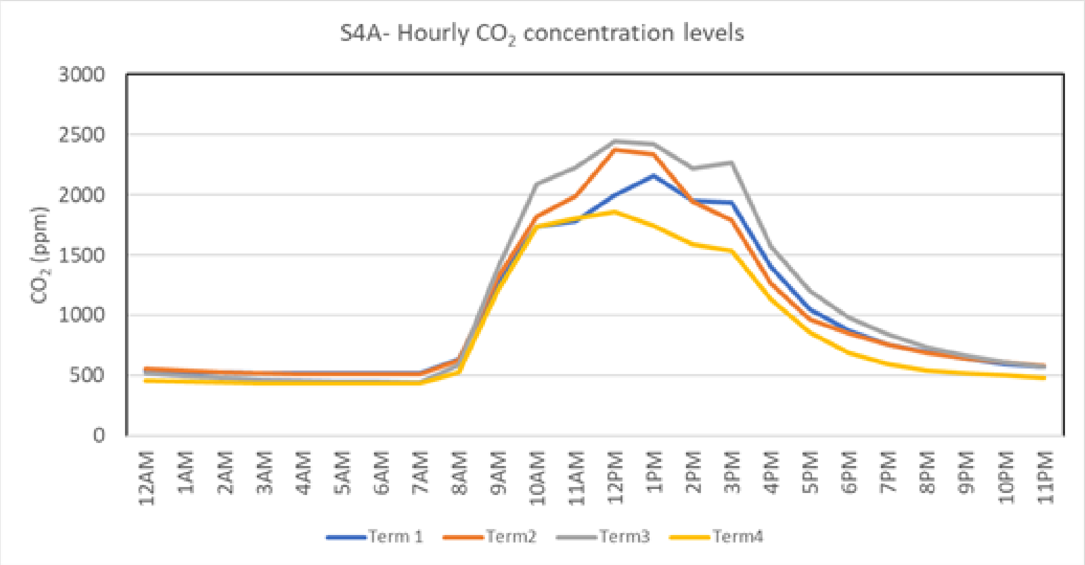

Figure 31 Hourly average CO_2 concentration levels for classroom S4A

The commonly referenced guideline value for CO_2 of 1000 ppm is based on the 650 ppm concentration difference with the outdoor CO_2 concentration of 350 ppm (ASTM, 2018). However, with outdoor CO_2 concentrations increasing (National Oceanic and Atmospheric Administration (NOAA), 2020), the indoor-outdoor concentration difference of 650 ppm would translate to a higher concentration than 1000 ppm. Comparing the mean measurement values of CO_2 concentrations (Figure 30) with the current annual average outdoor CO_2 concentration at Cape Grim (Australia) of 402 ppm (BoM and CSIRO, 2018), the difference of 255 ppm to 1833 ppm above outdoor levels indicate that IAQ in these ten school classrooms can be categorised as ‘Medium’ to ‘High’ (IDA 2, 400-600 ppm to IDA 1, less than 400mm) for School S5; ‘Medium’ (IDA 2, 400-600 ppm) for School S3; ‘Low’ (IDA 4, greater than 1000 ppm) to ‘Acceptable’ (IDA 3, 600-1000 ppm) for Schools S1 and S2; and ‘Low’ (IDA 4) with over 1000 ppm for S4, following the classifications of IAQ according to EN 13779 (CEN, 2007). The low CO_2 concentration levels for School S5 classrooms, classrooms S2B and S3B can be explained by the higher ventilations rates due to opening of windows and leaving doors open.

Supplementary fresh filtered air ventilation systems were fitted in Classrooms S1B, S2B, S3B S4B and S5B during the winter break (June-July 2019). Initially, G4 pre-filters were installed. Airflow rates were low and results show there were minimal variations in the CO_2 concentration levels in Terms 3 and 4 (Figure 30). Post Term 4, G4 pre-filters were supplemented with F7 filters and an addition of booster fans to increase the airflow rates in Classrooms S2B, S3B, S4B and S5B (Section 4.5). Classroom S1B was not fitted with the upgrade due to inadequate ceiling space. Figure 32 shows comparison of the CO_2 concentration levels after the upgrade in February-March 2020 for six school days. Only results for classrooms S2B and S4B are presented. Classroom S3B was not used as teaching space in Term 1, 2020 and data for Classroom S5B was not available. Results show a reduction in the peak levels of the inter-quartile range for both classrooms, by 200 ppm in S2B in comparison to Term 1 measurement levels. A greater reduction of 1136 ppm resulted in S4B in comparison to Term 2. The minimum levels in S4B also reduced by as much as 650 ppm.

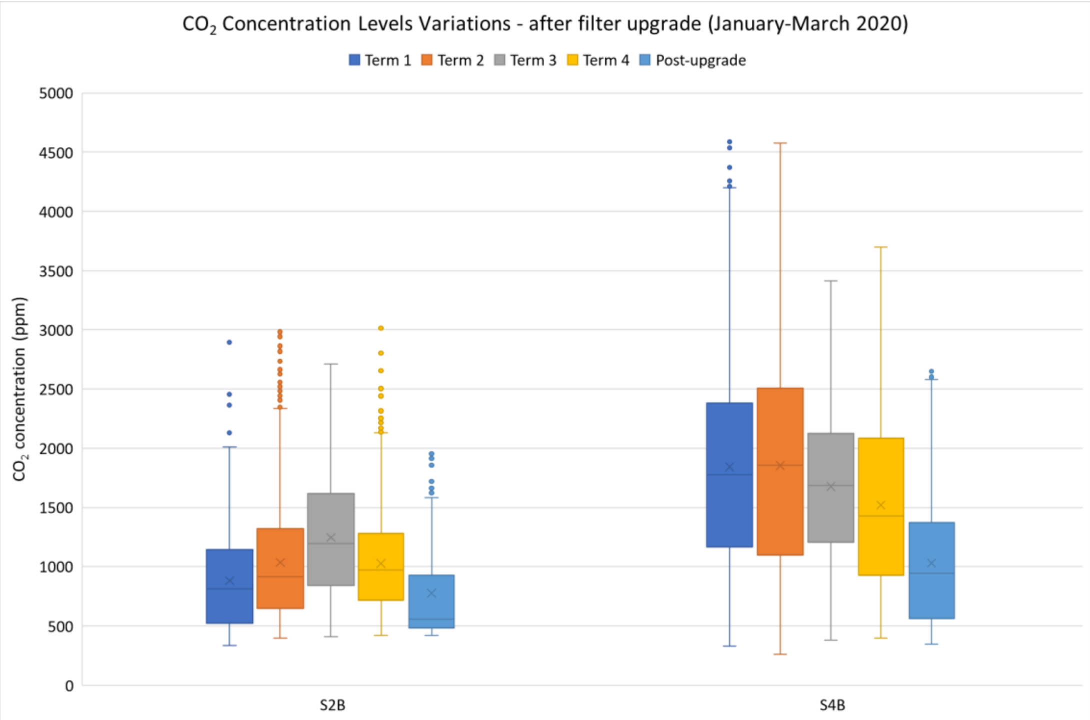

Figure 32 CO_2 concentration levels variations for intervention classrooms after upgrade

Ventilation Rates

The ten classrooms have floor area sizes ranging 55-81 m^2 and volume of 165-220 m^3 (Table 2) occupied by 15-27 school children (Table 4 and Table 5). The air change rate (ACH) was calculated using the peak-analysis approach based on a mass balance model (ASTM, 2018). The peak-analysis approach assumes that CO_2 concentration reaches steady state in classrooms (Luther et al., 2018). For analysis, the average CO_2 concentration recorded in the classrooms during the school hours was used as the steady-state value of CO_2 (C_s). The base outdoor concentration (C_o), was determined from the minimum indoor CO_2 concentration at the end of the long decay periods (weekends) (Roulet and Flavio, 2002). The CO_2 generation rates of 0.00285 Ls^{-1} for children and 0.0052 Ls^{-1} for the teachers in the occupied classrooms were used following ASTM D6245 (2018). These CO_2 generation rates correspond to the average ages of 6-11 for students and 21-50 for the teachers, with 1.2 *met* activity level (ASTM, 2018, Table 4, p5). The air flow rates in Ls^{-1} were calculated from the ACH.

The summary of the calculated ventilation rates, air change rates (h^{-1}) and air flow rates (Ls^{-1}) during school hours across the four school terms are shown in Table 5. The minimum CO_2 concentration values during the weekends (C_o) for the ten classrooms ranged from 281 ppm - 392 ppm in the weeks of Term 1 (monitored for 3-7 weeks), Terms 2 and 3 (10 weeks each), and Term 4 (11 weeks). It should be noted that due to equipment malfunction, weekend data was unavailable for S1B in Term 4 and S5A in Term 3 (Table S3, Part 8: Supplementary Information). Minimum concentration values during the hours of 7pm to 7am during the week were used

(Table 5). The indoor CO_2 concentrations in the classrooms during school week show that occupancy of the rooms influence the level of built up (Figure 31). This trend is also demonstrated during the school day, where increased CO_2 concentration levels correspond to class hours with decline after school hours. The minimum concentration values were deducted from the average CO_2 concentration (C_s) during school hours of 9:00am to 3:30pm.

The calculated ventilation rates ranged from 0.68 ACH to 4.28 ACH (Table 5). For S4 classrooms with the highest CO_2 concentrations, the air change rates during the four terms were 0.68 ACH to 1.0 ACH. The S3B classroom in school S3 with 'Medium' IAQ have air change rates of 2.59 ACH to 2.79 ACH, consistent across the four school terms. Both classrooms in school S5 with 'High' IAQ have 3.19 to 4.28 ACH in Term 3. The occupant behaviour in terms of opening and closing of doors and windows has a major influence on the ventilation rates. Windows and doors are left open in classroom S2B most of the time. Classroom S3B has the highest rate of ventilation throughout the year and as seen in Table 5 where the teacher leaves the windows slightly open and the door open to the corridor. Similarly, based on observations in School S5, the teachers tend to leave the doors open and these are open to the outside being located on the ground floor. Windows are closed in both S4A and S4B whereas doors are left open to the corridor. This did not help in reducing the CO_2 levels.

Table 4 Calculated ventilation rate values per student

School	Classroom	N	Ventilation rate ($Ls^{-1}\cdot p$)			
			T1	T2	T3	T4
S1	S1A	27	2.9	2.5	2.2	2.7
	S1B	26	2.9	2.7	2.5	2.7
	Average		2.9	2.6	2.4	2.7
S2	S2A	22	2.8	2.3	2.6	2.7
	S2B	22	4.8	4.3	3.2	4.4
	Average		3.8	3.3	2.9	3.6
S3	S3A	15	4.5	4.5	3.9	3.5
	S3B	26	4.6	4.9	4.6	4.9
	Average		4.6	4.7	4.3	4.2
S4	S4A	27	1.8	1.6	1.5	2.2
	S4B	27	1.9	1.9	2.1	2.6
	Average		1.9	1.8	1.8	2.4
S5	S5A	22	4.4	6.1	9.6	4.7
	S5B	17	4.2	6.9	10.2	4.5
	Average		4.3	6.5	9.9	4.6

Table 5 Calculated ventilation rate values of all classrooms across four (4) school terms

School	Classroom	N	*V* (m^3)	C_s (ppm)				C_o (ppm)				*Air changes per hour* (h^{-1})				*Air flow* (Ls^{-1})			
				T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
S1	S1A	27	202.4	1331	1518	1636	1443	364	378	363	391	1.41	1.20	1.08	1.30	79.6	67.5	60.4	73.1
	S1B	26	202.4	1323	1415	1508	1455	357	364	370	408*	1.36	1.25	1.16	1.25	76.7	70.5	65.1	70.8
S2	S2A	22	210.6	1319	1649	1471	1454	293	392	383	389	1.04	0.85	0.99	1.00	61.1	49.9	57.6	58.9
	S2B	22	210.6	882	1035	1247	1026	293	378	365	381	1.82	1.63	1.22	1.66	106.5	95.4	71.1	97.2
S3	S3A	15	176.2	912	1015	1069	1179	281	388	349	367	1.38	1.39	1.21	1.08	67.7	68.2	59.4	52.6
	S3B	26	164.7	925	958	977	945	311	371	352	366	2.64	2.76	2.59	2.79	120.7	126.2	118.6	128.0
S4	S4A	27	216.0	1943	2177	2235	1648	368	372	362	371	0.81	0.71	0.68	1.00	48.9	42.6	41.1	60.3
	S4B	27	219.5	1843	1855	1676	1519	320	373	347	310	0.83	0.85	0.95	1.04	50.5	51.9	57.9	63.6
S5	S5A	22	178.0	980	827	671	970	333	360	375*	363	1.96	2.72	4.28	2.09	96.9	134.3	211.8	103.3
	S5B	17	195.0	1019	784	657	965	334	375	377	335	1.31	2.19	3.19	1.42	70.7	118.5	173.0	76.9

*weekend data unavailable, used 7pm to 7am after school hours

The average calculated ventilation rate per person in this study ranged from 1.8 Ls^{-1} to 9.9 Ls^{-1} (Table 4). These ventilation rates were higher in comparison to a similar study of naturally ventilated schools in Brisbane (Laiman et al., 2014). ANSI/ASHRAE Standard 62.1 recommends a minimum ventilation rate of 5 Ls^{-1}·person for classrooms (ASHRAE, 2019a). The resulting ventilation rates per person in this study as shown in Table 4, with the exception of the two classrooms in School S5, were less than 5 Ls^{-1} per student indicating insufficient ventilation of the classrooms across the seasons. School S4 shows average ventilation rates of 1.8 to 2.4 Ls^{-1} per student. Whereas, both classrooms in school S3 have ventilation rates ranging from 4.6-4.9 Ls^{-1} per student which marginally meet the minimum ASHRAE Standard 62.1 requirement. The two classrooms in School S5 have average ventilation rates of 4.3 to 9.9 Ls^{-1} per student meeting the recommended minimum ventilation rate. The classrooms in School S3 also exceeds the specified ventilation rate of 4 Ls^{-1} per child established in the SINPHONIE project (Csobod et al., 2014), whereas this specified rate marginally aligns with those found in S2, with average values ranging from 2.9 Ls^{-1} to 3.8 Ls^{-1}.

Particulate Matter

$PM_{2.5}$

The indoor to outdoor ratio of $PM_{2.5}$ concentrations in the intervention classrooms where the ventilation system was installed are shown in Figure 33. When the ratio is above 1, it means more particles exist in the indoor space in comparison to outdoor. It was noted that indoor $PM_{2.5}$ levels followed the outdoor profile suggesting that the main particle sources are from outside. S2 and S5 have lower indoor-outdoor ratio during the four school terms. School S1 recorded high indoor-outdoor ratio in Term 3 and School S3 recorded high indoor-outdoor during Term 1. This elevated ratio could be attributed to the student activities mainly conducted indoors due to wintry outdoor conditions and due to lower outdoor PM levels. Outdoor $PM_{2.5}$ levels generally increased in the morning drop off period, afternoon pick up time and when students were outside playing in the playground. However, no consistent patterns were observed between various seasons.

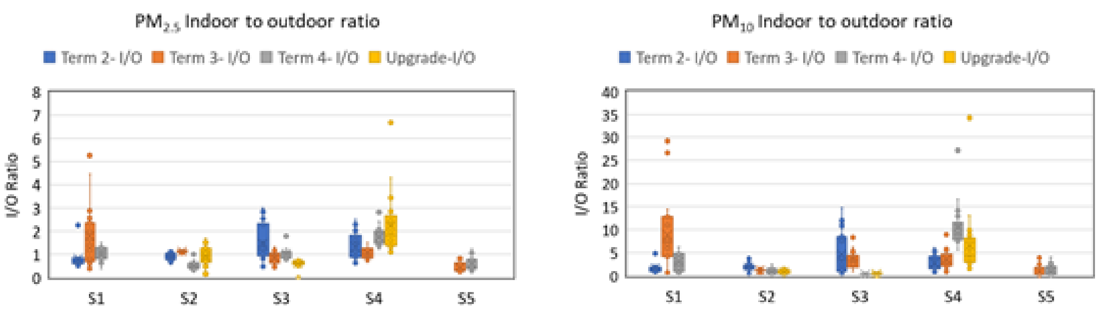

Figure 33 Particulate matter, $PM_{2.5}$ and PM_{10}, indoor/outdoor ratio in five (5) schools

PM_{10}

PM_{10} consist of particles of any substances that are less than 10 micrometres. The presence of occupants is an important source of PM_{10} indoors. Looking at the profiles of indoor and outdoor

PM$_{10}$ across the four school terms, the profiles did not demonstrate similar patterns showing that the sources could be from inside rather than outside. A contributing factor could be the activities of the students indoors. Schools S1 and S3 showed higher PM$_{10}$ levels in Terms 3 and 2, respectively. Outdoor PM$_{10}$ levels were much lower during these periods, probably because the measurement was conducted on a rainy day and dust particles are settled rather than suspended in the air. For School S4, Term 4 indoor-outdoor ratios were higher mainly because it was a windy day and particles might have seeped from outside to inside.

The outdoor PM levels depend on several factors including the geographical location, topography, wind speed and direction, rain, proximity to PM emission sources such as traffic, etc. WHO (2006) recommends maximum levels of 20 µm/m^3 per year and 50 µm/m^3 per 24-hour for PM$_{10}$ levels; for PM$_{2.5}$, the recommended levels are not more than 10 µm/m^3 per year and 25 µm/m^3 for 24 hours. As there are no guidelines for indoors, the guidelines for outdoor PM levels are followed for indoors. It was found that 24 hours average were within the WHO guidelines for all the schools. It was noted that indoor-outdoor levels were lower for School S2 and higher for School S4. This is mainly because outdoor PM levels were lower in School S4. Lower indoor-outdoor ratio suggests lower indoor pollutant levels and tight envelope in School S2. The location of particle sensors outdoor can also influence the measurement readings. Identification of specific sources of particles would require further control experiments targeting particular activities, extended to outside school hours.

Pathogens

Indoor microbial concentration is dependent on several factors including the extent of bacteria and mould reservoirs by occupants and ventilation. The main sources of bacteria indoors are outdoor air, occupants and indoor bacterial growth. The indoor-outdoor relationship can be used as a preliminary indicator of the possible relationship between the two environments. The comparison of bacteria count before and after the installation of the ventilation system is shown in Figure 34a.

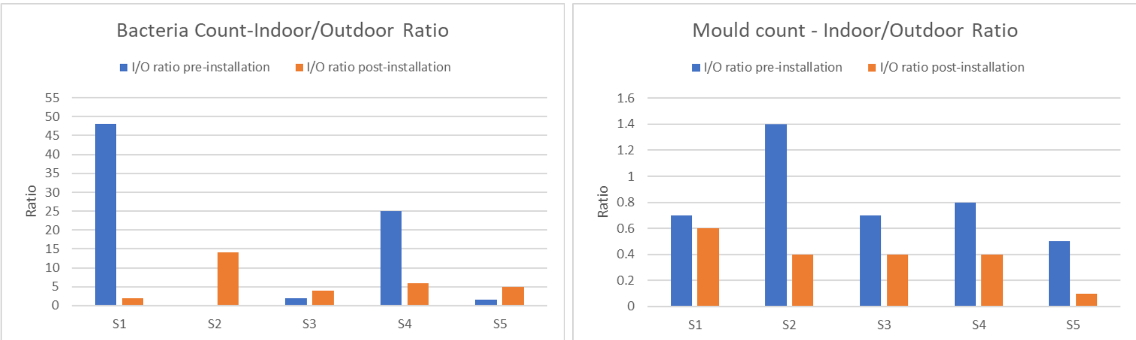

Figure 34 (a) Comparison of bacteria levels (b) mould levels for five (5) schools

The results showed that indoor outdoor ratios were lower in S1 and S4 for post installation, whereas for S2, S3 and S5, it was higher post installation. It was noted that outdoor levels were much lower in May-June2019 in some schools when the pre-installation sample was taken, in comparison to July-September 2019 when the post installation sample was taken. It is not possible to identify the type of bacterial species in the sample without conducting additional testing. Furthermore, most sampling methods do not distinguish between mould species. For a proper understanding of the sources of these microbials, multiple samples should be collected for a longer period.

The comparison of mould before and after the installation of the ventilation system is shown in Figure 34b. The post installation ratios were lower for all the schools. For mechanically ventilated buildings, when the indoor fungi count is more than half (>0.5) of the outdoor fungi count, there could be potential elevated health risks (Kemp and Neumeister, 2010, p9). For S2, the indoor count is around 1.4 more than the outdoor count, and there could be potential elevated health risks in S1, S2, S3 and S4. However, there is no conclusive evidence to state that the ventilation system influenced the microbial count as there was no significant improvement in the ventilation rates in Terms 3 and 4 after the installation.

5.2 Evaluation of student attention and concentration

To evaluate student performance, d2 Attention test was used. This is a timed test to estimate individual attention and concentration performance such as processing speed and quality of performance (Brickenkamp and Zillmer, 1998). The test is administered to the students via a one-page, paper and pencil test comprising 14 lines of the characters ‘d’ and ‘p’ with one to four dashes. The task is to find and cross out as many target characters as possible (a ‘d’ with a total of two dashes placed above and/or below) per line in a limited time of 20 seconds – every 20 seconds to move on to the next line.

The test includes four performance parameters: total number of items processed (TN), the number of mistakes due to omission (E1), errors of commission (E2) and concentration performance (CP). TN, representing reaction time and speed, is a highly reliable measure of attention allocation, processing speed, amount of work completed and motivation and measures the performance of all processed items regardless of their relevance. E1 occurs when relevant items (‘d’ with two dashes) are not crossed out, and it is a relatively common mistake and sensitive to attentional control, rule compliance, accuracy of visual scanning, and quality of performance. E2 occurs when irrelevant letters are crossed out. It is a less common error and related to inhibitory control, rule compliance, accuracy of visual scanning, carefulness, and cognitive flexibility. CP is obtained by subtracting E2 from the number of the correctly crossed out relevant items. It is highly reliable and used in paediatric populations as an index for the accuracy of performance and coordination of speed (Rivera et al., 2017; Wassenberg et al., 2008).

A total of 555 d2 Attention test was collected from ten classrooms in five schools over the four school terms in 2019. The students were aged between 8 and 16 years old, reporting an average of 11 years old (Table 6). Majority of the students were aged between 10 and 12 years old (N=405, 73%). The gender mix of the students was that 54.6% were male and 45% were female. Most of the students were right-handed (N=494, 89.5%).

Table 6 Background of the students

	N	%
Gender		
Male	303	54.6
Female	250	45.0
Total	553	100.0
Age		
8	21	3.8
9	35	6.4
10	152	27.8
11	178	32.5
12	75	13.7
13	24	4.4
14	33	6.0
15	23	4.2
16	6	1.1
Total	547	100.0
Handedness		
Left	58	10.5
Right	494	89.5
Total	552	100.0

The number of participants were steady across the terms (Table 7), demonstrating some classrooms presented a very high level of participation (S1B, S2A, S2B) and others showed a medium to low level of participation. It is noted that the number of students per class is around 15-27 students. Although the students ages varied, particularly due to one secondary school's involvement (S5), the results of the test do not seem to be different from those of younger students in four primary schools. Overall, the test scores tended to increase over time due to students' familiarity with the test.

Figure 35 demonstrates the distribution of TN scores in ten classrooms across the four school terms. Students demonstrated improvement in the Terms 3 and 4 when compared to the previous two terms. Some showed a significant improvement from Term 1 to Term 2 (S2A, S2B, S4A, S4B) which can be interpreted that students understood the rules of the test better in their second time. Unexpectedly, the student ages did not seem to influence the quantity of work (reaction time and speed). S5 is the only secondary school whose students were aged between 12 and 16 years old. The distribution of TN scores does not show any difference among other primary schools. Furthermore, despite the improvement in student performance in Term 3 and Term 4 it is hard to interpret that the ventilation system influenced the student performance as there was no significant improvement in the ventilation rates in Terms 3 and 4 after the installation.

Table 7 Mean scores of d2 Attention test (N=555)

		S1		S2		S3		S4		S5	
		A	B	A	B	A	B	A	B	A	B
Term 1	N	10	14	20	18	5	12	15	17	14	16
	TN	440.2	362.9	370.5	384.8	445.8	480.8	391.4	384.6	422.1	436.8
	E1	8.1	8.9	6.3	10.1	9.0	14.6	10.2	7.8	23.4	45.1
	E2	9.1	11.2	8.2	6.9	10.8	23.4	12.0	10.2	10.0	15.4
	CP	169.5	132.9	141.0	145.2	164.6	164.3	143.3	143.6	171.1	170.1
Term 2	N	8	19	21	19	7	12	11	13	12	13
	TN	452.3	393.5	472.6	495.5	462.7	509.2	508.1	488.5	506.2	475.0
	E1	8.8	15.8	8.4	12.3	17.6	8.5	9.3	9.5	12.8	18.0
	E2	8.4	17.9	12.0	14.1	10.3	12.9	17.6	9.8	13.0	10.9
	CP	175.5	131.2	179.1	185.5	169.9	194.2	191.6	187.0	190.9	173.2
Term 3	N	11	21	20	21	6	11	12	13	12	14
	TN	521.9	437.3	468.2	496.1	514.7	572.6	485.6	553.6	500.2	476.4
	E1	10.5	10.1	7.6	12.7	8.2	6.9	12.4	10.6	13.1	14.4
	E2	5.5	9.7	9.4	19.6	11.5	11.9	14.9	13.9	11.5	6.7
	CP	207.1	164.8	181.0	180.4	200.2	234.3	181.4	216.8	189.3	181.1
Term 4	N	11	19	21	16	7	10	14	13	11	16
	TN	538.7	456.5	551.6	547.5	525.1	578.3	557.4	560.9	546.8	510.9
	E1	7.3	9.8	12.4	15.1	11.9	7.5	17.4	14.1	15.9	18.3
	E2	6.1	15.3	13.6	12.4	6.4	11.4	20.6	11.3	7.5	6.6
	CP	221.1	166.7	214.9	211.4	208.9	235.9	205.6	222.5	215.0	195.1

E1 and E2 represent the errors and mistakes that students made in the test. While E1 occurs due to omission when relevant items are not crossed out, E2 occurs due to commission when irrelevant letters are crossed out. Figure 36 and Figure 37 demonstrate the distributions of the errors across the four school terms. There seems to be no significant pattern found in all ten classrooms. There was a wide range distribution of E1 scores in S5B in Term 1. Again, it can be interpreted by students' improvement in rule compliance after taking the test first time.

CP can be considered a reliable parameter for the accuracy of performance and coordination of speed. With consistency the distribution of CP scores shows the similar pattern to that of TN scores in ten classrooms across the four school terms (Figure 38). Students demonstrated improvement in Term 3 and Term 4 when compared to the previous two terms in all classrooms. Some showed a significant improvement from Term 1 to Term 2 (S2A, S2B, S4A, S4B) which can be interpreted that students better understood the rules of the test in their second time. Similarly, the student ages did not seem to influence the accuracy of work either.

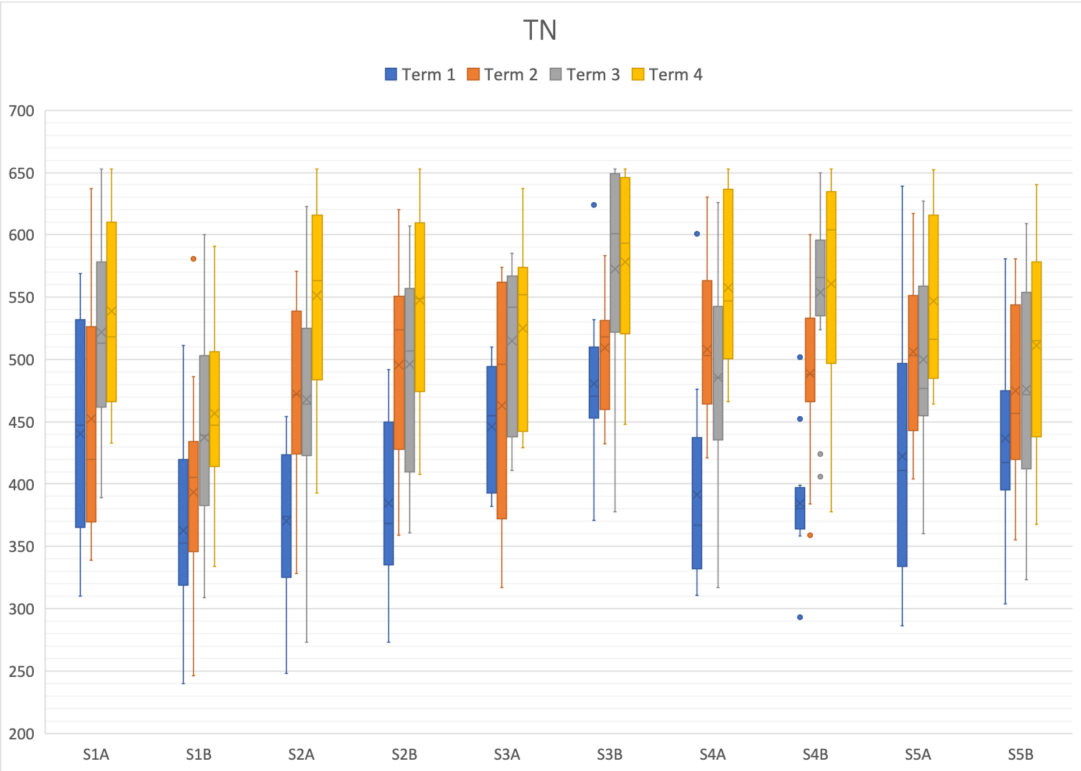

Figure 35 Distribution of TN scores across school terms

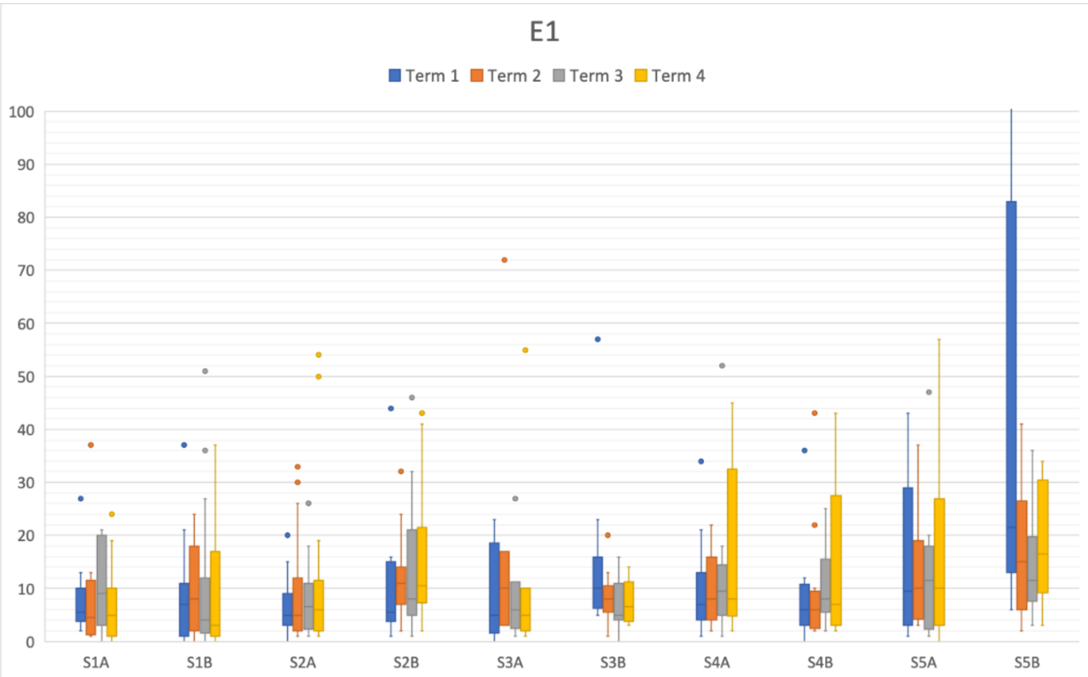

Figure 36 Distribution of E1 scores across school terms

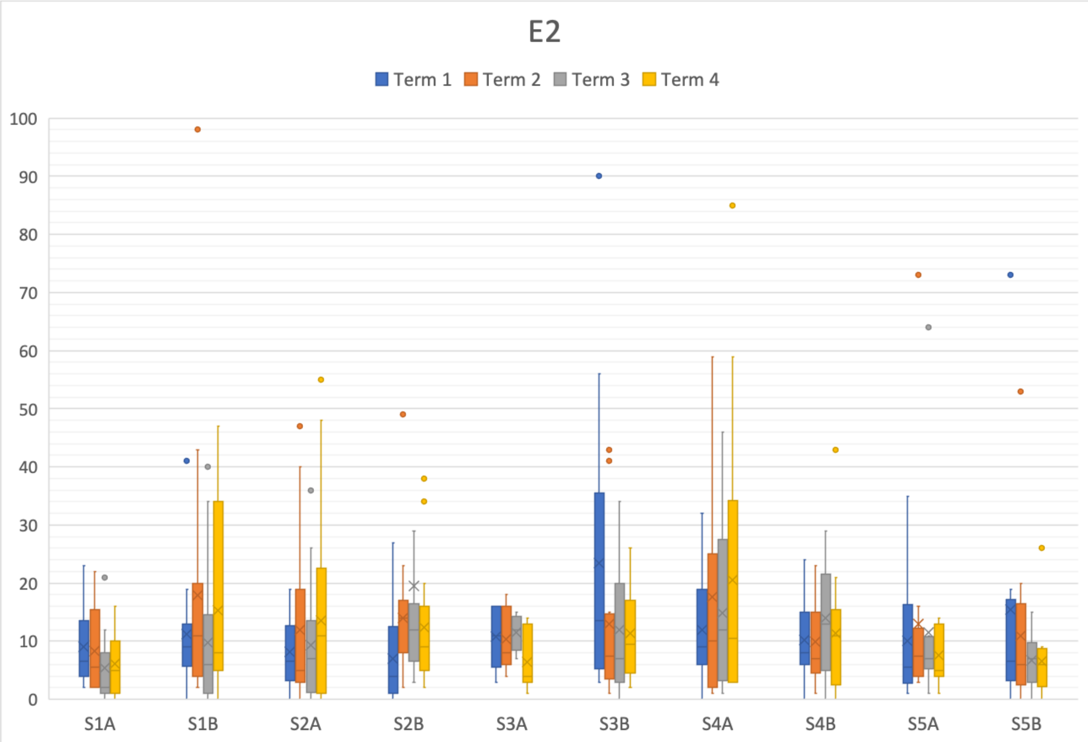

Figure 37 Distribution of E2 scores across school terms

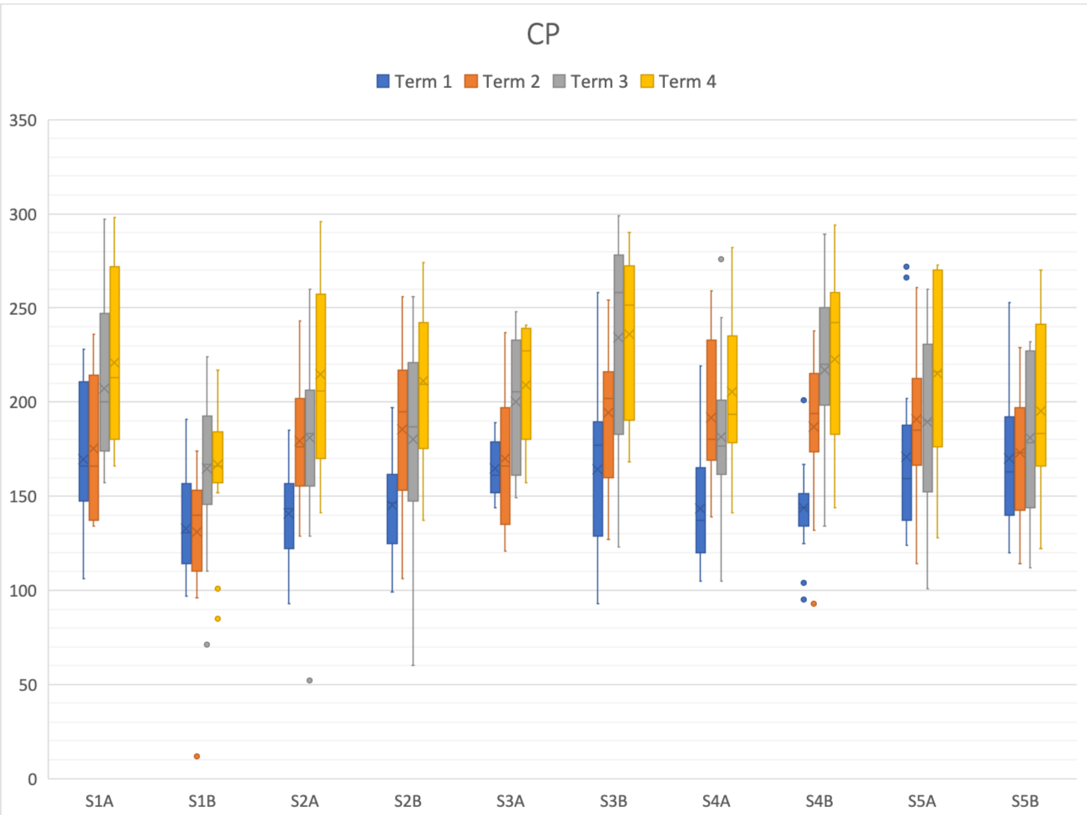

Figure 38 Distribution of CP scores across school terms

Accuracy and reaction time can be considered two main parameters to measure task performance quantitatively. Previous research adopted simulated tasks such as addition, text typing and neuro-behavioural tests to measure the task performance in a controlled experimental environment (Geng et al., 2017; Jiang et al., 2018; Lan, Li et al., 2011; Lan, L. et al., 2012). In this research, the results showed that the four performance parameters, TN (reaction time, speed), errors of omission (E1), errors of commission (E2) and concentration performance (CP) in natural classroom settings across the whole year.

The age of the students can be an influential factor to measure student performance. There could be an individual difference upon their age, however, there seems to be no significant difference found in the class collective results. Furthermore, although there is some inconsistency, in general, previous research found that student performance is to be optimal when children are about 10 years old (Klenberg et al., 2001; Klimkeit et al., 2004; Rebok et al., 1997; Wassenberg et al., 2008). Wassenberg et al. (2008) reported no age-related improvement was found for the level of the omission error (E1), indicating complete development in or before the second grade, the commission error (E2) had stabilized in the fourth grade, and processing speed (TN) continued to improve into the sixth grade. In this research, the majority of the students were aged at 10 and 12 years old and they did not show any significant difference in the performance parameters upon their age.

Statistical analysis was conducted to examine if a relationship can be established between IAQ and student performance. Seven indoor condition parameters namely air temperature, relative humidity, CO_2 concentration, air velocity, mean radiant temperature (MRT), $PM_{2.5}$ and PM_{10} were selected for correlation. It is noteworthy that three schools among the five schools were selected to ensure consistency in geographical location and student age. One primary school in regional Victoria and a secondary school were excluded for statistical analysis. The results of student performance tests established a low to moderate correlation between ventilation rates and student performance across the school terms, particularly speed and accuracy, demonstrating that IAQ does impact student concentration performance (Part 8: Supplementary Information, Table S4). Stepwise multiple regression analysis showed that 16.1% of the variance in TN is explained by the four indoor parameters of $PM_{2.5}$, mean radiant temperature, relative humidity and air velocity (Part 8: Supplementary Information, Table S5).

Part 6: Results – Aged Care Homes

6.1 Indoor Conditions

Thermal Environments

The temperature variations in the ten rooms of the five aged care homes monitored during the four seasons are shown in Figure 39: Season 1 – January to February 2019, Season 2 – March to May 2019, Season 3 – June to August 2019 and Season 4 – September to November 2019. The temperature across the aged care homes did not vary significantly in various seasons. The average temperatures during various seasons ranged between 20.6°C and 23.9°C. Average temperature for Seasons 1 (summer) and 2 (autumn) were around 1°C higher than Seasons 3 (winter) and Season 4 (spring). AC1B had the largest variation of indoor temperature across the four seasons, where minimum was around 18°C and maximum was around 28°C during Season 1. During Season 3, minimum and maximum temperatures were 13°C and 30°C respectively. This room was only occupied couple of hours during the day and heaters and air conditioners were switched off during the unoccupied period.

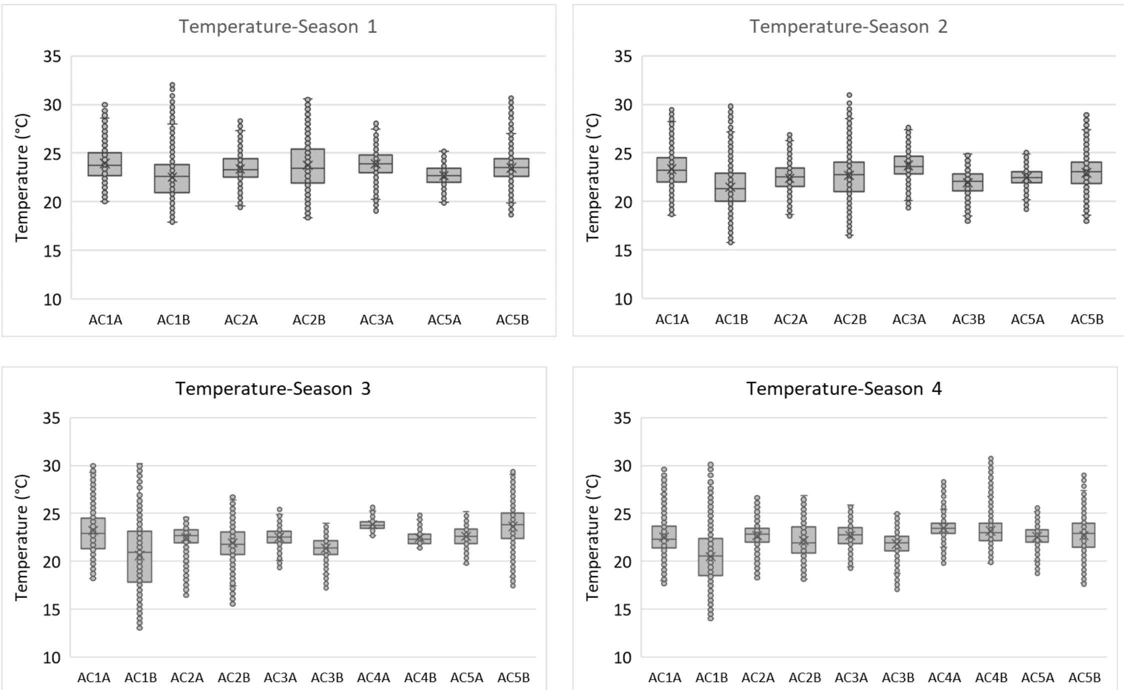

Figure 39 Air temperature (°C) variations across four (4) seasons

The relative humidity variations across the four seasons shown in Figure 40, ranged from 46-62RH% during summer, and 41-54RH% during autumn. The average RH values varied between 35-43RH% during winter and 40-48RH% during spring.

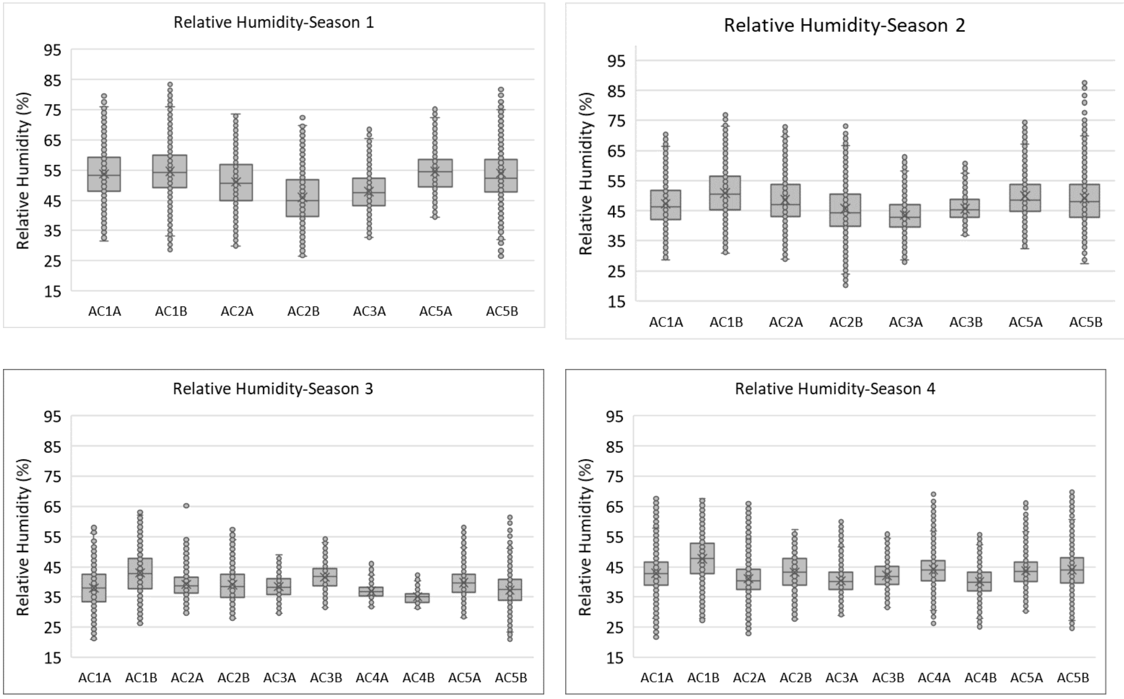

Figure 40 Relative humidity (RH%) variations across four (4) seasons

CO_2 Concentration Levels

The carbon dioxide concentration levels for the ten rooms across various seasons are shown in Figure 41. The range of carbon dioxide concentration levels in the five aged care homes during Season 1 (January-February 2019) and Season 2 (March- May 2019) respectively, represent the pre-installation period. Seasons 3 and 4 represent the post installation period. As discussed in Section 3.2, indoor CO_2 concentrations above ~1000 ppm are generally regarded as indicative of unacceptable ventilation rates (ASTM, 2018).

CO_2 levels were significantly high in AC1B (Figure 41) during all seasons where readings above 1000 ppm were noted on many occasions. The highest level was found to be around 2000 ppm. The CO_2 levels normally increase with the number of occupants. During the monitoring period, it was observed that the number of occupants in the room varied from unoccupied to 33 people. On rare occasions such as festive seasons and special events, up to 52 people gathered in one of the rooms.

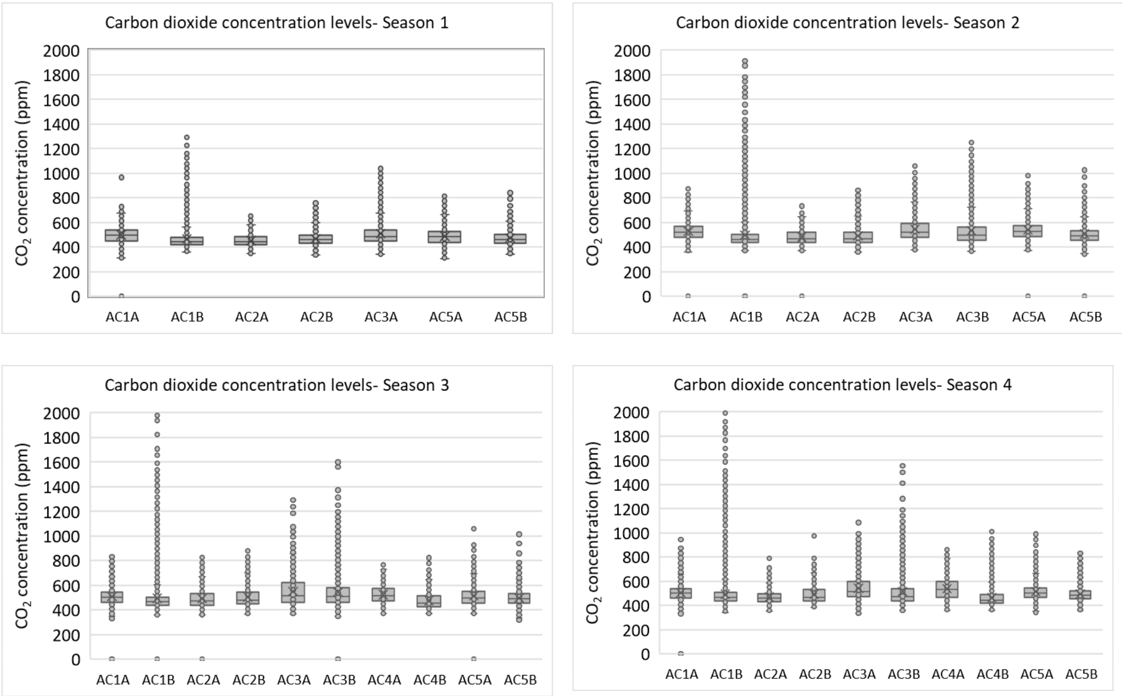

Figure 41 CO_2 concentration levels variations across four (4) seasons

The ventilation systems in the three facilities (AC1, AC2 and AC3) were upgraded by increasing the airflow rate and by adding an F7 filter with the existing G4 pre-filter. Figure 42 shows the CO_2 concentration levels after the upgrade for a single day. Comparing with Figure 41, the peak CO_2 levels reduced as a result of increased ventilation.

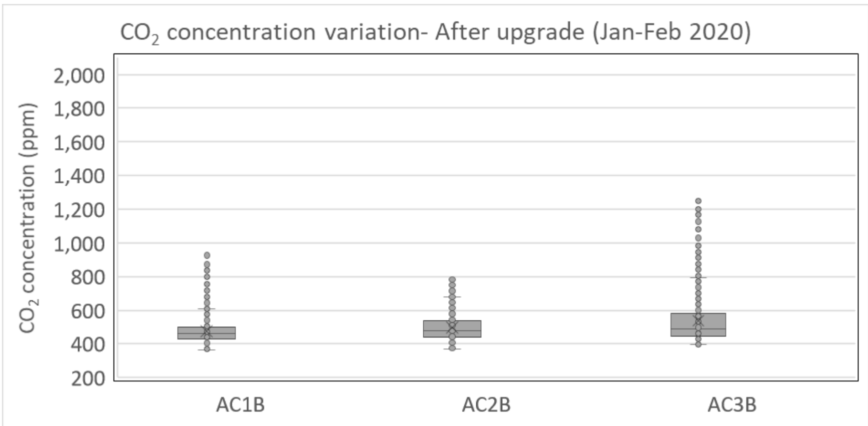

Figure 42 CO_2 concentration levels after ventilation system upgrade

Ventilation Rates

The ten rooms have floor area sizes ranging 48-192 m^2 (Table 3) and volume of 154-616 m^3 (Table 8). Similar to the schools, the air change rate (ACH) was calculated using the peak-analysis approach. The CO_2 generation rate 0.0052 Ls^{-1} for each resident in the occupied room was used following ASTM D6245 (2018).

Table 8 Calculated ventilation rate values of aged care homes for four (4) seasons

Aged care home	Room	*n*	*V* (m^3)	C_s (ppm)				C_o (ppm)				*Air changes per hour* (h^{-1})					*Ventilation rates*				
				S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**After upgrade**	**S1**	**S2**	**S3**	**S4**	**After upgrade**
AC1	AC1A	1-9	154	765	517	634	703	362	362	362	332										
	AC1B	1-22	169	1044	1203	656	632	369	369	361	332		2.9			2.01		6.24			9.45
AC2	AC2A	19-21	616	558	765	605	522	362	362	362	354	3.26	1.43	2.5	3.62		26.53	12.9	21.4	30.95	
	AC2B	6-8	269	654		668	635	369		366	385		NA			2.46					14.13
AC3	AC3A	14-25	363	714	715	822	1085	376	376	367	334	3.81	2.13	1.7	1.3		15.38	15.34	11.43	6.92	
	AC3B	15-25	355	937	992	976	1300	366	366	348	358	2.31	2.02	1.6	0.84	1.7	9.11	8.31	8.28	5.52	8.36
AC4	AC4A	6-33	543	785	762	704	794	359	362	359	359		1.72	3.3				13	15.07		
	AC4B	16-52	576			741	1244	362		362	362	NA	NA	1.37	1.92				13.72	5.9	
AC5	AC5A	6-12	429	726	731	630	585	371	371	370	342	1.23	1.21	2.01			14.65	14.44	20		
	AC5B	5-12	260	587	429	622	590	342	342	319	361			2.85	3.77				17.16	22.71	

The summary of the calculated air change rates (h^{-1}) on the selected days during the four seasons are shown in Table 8. The minimum CO_2 concentration values (C_o) for the ten rooms ranged from 332 ppm-385 ppm. As the number of residents using the space vary considerably every day, CO_2 concentration levels of a single day during maximum occupation was used for ACH calculation. The minimum concentration values were deducted from the maximum CO_2 concentration (C_s). The calculated air change rates ranged from 0.84 ACH to 3.81 ACH (Table 8). ACH levels varied significantly in different seasons. Lowest ACH level of 0.84 was calculated for AC3B during Season 4. The ventilation rates ranged from 5.52 Ls^{-1} person to 30.95 Ls^{-1} per person. After the system upgrade in the intervention rooms, the ACH calculated were 2.01, 2.46 and 1.7 for AC1, AC2 and AC3 and respectively. The corresponding ventilation rates per person were 9.45 Ls^{-1}, 14.13 Ls^{-1} and 8.36 Ls^{-1} respectively for AC1, AC2 and AC3.

Particulate Matter

Similar to the schools, the concentrations of particulate matter, $PM_{2.5}$ and PM_{10} in the five aged care homes were monitored and are presented as indoor to outdoor ratio.

$PM_{2.5}$

Figure 43 shows the indoor to outdoor ratio of $PM_{2.5}$ concentrations in the intervention rooms of five aged care homes. When the ratio is above 1, it means more particles exist in the indoor space in comparison to outdoor. As shown in Figure 43, there was no noticeable pattern observed across the seasons and this could be due to the limited occupancy and activities during the monitoring period. However, in Facility AC2, the ratio was found to be high during Season 1 and this ratio went up to 4.5. The indoor peaks were observed at around 11 am and 3 pm. This could be due to some local activities near the dust monitor such as people gathering or cleaning. Similarly, the ratio in Facility AC3 during Season 2 was higher. It was observed that around 25 people were present in the room during the measurement participating in the ‘happy hour’ activities in Season 2.

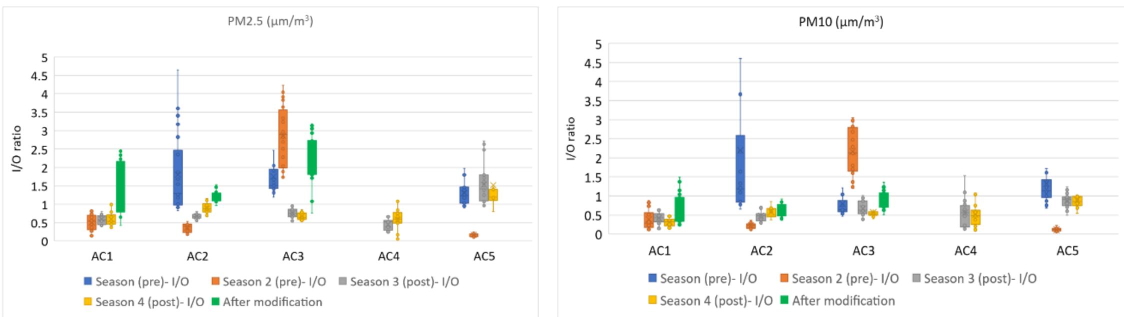

Figure 43 Particulate matter, $PM_{2.5}$ and PM_{10}, indoor/outdoor ratio in aged care homes

Looking at the indoor to outdoor ratio after modifying the system (Green colour bar in Figure 43), it can be seen that the $PM_{2.5}$ ratio generally increased in all the aged care homes. This could be because of the activities and people movement in the room or due to the re-suspension of particles as a result of higher air change rate. In Facility AC1, the indoor $PM_{2.5}$ levels were found to be more than outdoor $PM_{2.5}$ levels after the modification. The selected intervention room in Facility AC1 is smaller and more confined compared to other facilities and this could have contributed to such outcomes. Also, the room was occupied and was used for training the aged care staff on the day of measurement.

PM_{10}

PM_{10} consists of particles of any substances that are less than 10 micrometres. The presence of people is an important source of PM_{10} indoors. It can be seen from Figure 43 that Facility AC2 had a high indoor-outdoor ratio of PM_{10} concentration in Season 1 similar to $PM_{2.5}$ which could be because of some local movement or activities next to the dust monitor. In Season 2 in Facility AC3, indoor PM_{10} were higher than the outdoor levels due to the 'happy hour' activities during the measurement period. Generally, there was no significant difference in the indoor-outdoor ratio after the modification. In Facility AC1, indoor levels were very consistent and did not vary with the outdoor.

Pathogens

The comparison of bacteria before and after the installation of the ventilation system is shown in Figure 44a. It is to be noted that the sampling was done before the filter modification. The results show that the indoor-outdoor ratio reduced in the post-installation stage for all except in Facility AC1. One of the possible reasons for this could be that the outdoor levels were much lower in June when the pre-installation sample was taken, in comparison to September when the post-installation sample was taken. However, in the case of Facility AC1, the post-installation measurement showed higher indoor-outdoor ratio. It is not possible to identify the type of bacterial species in the sample without conducting additional testing. Furthermore, most sampling methods do not distinguish between mould species. For a proper understanding of the sources of these microbials, multiple samples should be collected for a longer period.

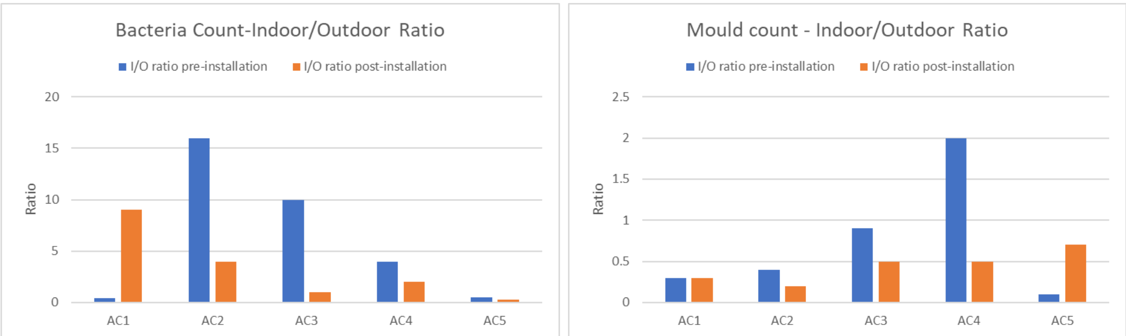

Figure 44 Comparison of (a) bacteria levels and (b) mould levels for five (5) aged care homes

The comparison of mould before and after the installation of the ventilation system is shown in Figure 44b. The post-installation ratio was lower than pre-installation ratio in Facilities AC2, AC3 and AC4. However, the post- installation ratio was slightly higher for Facility AC1 and much higher for Facility AC5. For Facility AC3, the indoor-outdoor ratio was higher (~0.9) in comparison to the other facilities as shown in the pre-installation graph (Figure 44b). For mechanically ventilated buildings, when the indoor fungi count is more than half (>0.5) of the outdoor fungi count, there could be potential elevated health risks (Kemp and Neumeister, 2010).

Part 7: Discussions and Conclusions: Summary of Findings

This study investigated IAQ in schools and aged care homes using field monitoring extended for more than a year. The monitoring provided a comprehensive understanding of the actual conditions of the selected spaces in different settings and an overview of the various physical and operational factors affecting IAQ in these facilities. The average CO_2 concentration levels in the different school classrooms ranged from 912 to 2235 ppm, while the maximum concentration levels reached up to 5000 ppm during certain times of the occupied hours. The air change rates ACH) ranged between 0.68 to 4.28 and were below the recommended standards in seven out of the ten classrooms investigated. The PM levels were within the guidelines stipulated by the World Health Organization. The PM levels were found to be very much influenced by the activities and movement of students inside the room and the opening and closing of windows and doors. The results of student performance tests established a low to moderate correlation between ventilation rates and student performance across the school terms, particularly speed and accuracy, demonstrating that IAQ does impact student concentration performance.

In the aged care homes the occupancy rate varied significantly during the day and maximum CO_2 concentration levels reached up to 2000 ppm when the rooms were moderately or fully occupied. The ACH ranged from 0.84 to 3.81 and ventilation rates ranged from 5.52 Ls^{-1} per person to 30.95 L^{s-1} per person. The results of the 14-month long monitoring showed that the addition of fresh filtered air ventilation system reduced the indoor CO_2 concentration levels by as much as 1000 ppm, particularly with the system upgrade. However, in contrast, no reduction was observed in the PM concentration levels. In fact, the PM concentration levels were found to be very much influenced by the local activities and movement of people inside the room. Identification of specific sources of particles would require further control experiments targeting activities, extended to outside school hours. Pathogen analysis results showed variation of bacteria and mould levels in different seasons both outdoors and indoors. Mould levels were higher than the recommended levels in some of the facilities. However due to the limited number of samples collected it was difficult to comment on what factors could have contributed to the microbial concentration levels.

The main contributions of the study are:

- This study provided information on the actual thermal and air quality performance of school classrooms and aged care homes located in different geographic locations in Victoria; and improved the understanding on how various design and operating conditions affect ventilation rates and air quality in various seasons.
- The study also provided insights about the interdisciplinary aspects of IAQ in school classrooms which were not previously explored in Australian conditions and demonstrated a method for analysing the effect of IAQ on students' learning performance.

- The findings could be used to inform guidelines on building construction, envelope air tightness, cooling policy and ventilation standards. The findings can also inform the operation and maintenance of classrooms and HVAC systems including filter grade and fresh air intake.
- The results of this study indicate the need to further investigate the indoor conditions and air quality in school classrooms for providing guidelines for building construction, envelope airtightness, cooling policy and ventilation standards.

Below are some of the limitations of the study and some recommendation for future studies:

- Aged care health survey: Even though this study intended to collect the aged care resident's perception of air quality using a questionnaire, it was noted after the first season, that most of the residents were not able to complete the questionnaire accurately. Subsequently, the research team tried to get information about the health data in the form of monthly incident reports such as number of infections and hospital visits during the study period. However, this information was not readily available in most of the aged care homes. Future studies can include collection respiratory health conditions using a standard questionnaire to understand the effect of indoor air quality on health.
- Aged care bedrooms: In this study only common rooms in the aged care homes were monitored while most of the residents spend longer time in their bedrooms. Future studies should be extended to the bedrooms to understand the impact of air quality in bedrooms.
- Student learning performance assessment: In this study, student results in the d2 Attention test show low to moderate correlation between the ventilation rates and student performance across school terms. Findings indicate that the variance in the concentration performance may also be affected by $PM_{2.5}$, indoor conditions such as mean radiant temperature, relative humidity and air velocity and further effects of air temperature and CO_2 concentration levels. The d2 Attention tests showed interesting results that should be explored using a larger sample to develop correlations to estimate student performance in mechanically controlled and naturally ventilated conditions.
- Pathogen sampling: In the current study, only two samples were collected from each facility for the whole year. It is recommended that additional samples be collected for an extended period to get a comprehensive understanding of the effect of various factors on pathogens.
- PM measurement with systematic monitoring of indoor activities: It was noted that PM concentration levels were influenced by the local activities within the room. For further studies, close monitoring of indoor activities with existing HVAC system turned off is required to understand the influence of ventilation on particle concentration.
- Bush-fire smoke events: PM measurements did not capture the bush-fire smoke events in Victoria. It is recommended that future study investigate the PM levels during the bush fire smoke events by replacing the filters with more efficient ones such as HEPA filters.
- It is recommended that the study be extended to other states in Australia to understand the impact of different climatic conditions on indoor air quality.

Part 8: Supplementary Information

Table S1 Instrument and sensors specifications

Type of instrument	Parameter	Measuring range and accuracy
HOBO MX1102	Air temperature (°C)	±0.21°C from 0° to 50°C
	Relative humidity (%)	±2% from 20% to 80%
	CO_2 concentration (ppm)	±50 ppm ±5% of reading at 25°C
Aerocet Handheld Particle Counter Model 531S	PM2.5 PM10	± 10% ± 10%
Testo 480	Air temperature (°C) Relative humidity (%) CO_2 concentration (ppm) Globe temperature (°C) Air velocity (ms^{-1})	0 to +50°C, ±0.5°C 0 to 100RH%, ±(1.8RH% + 0.7% or measured value) 0 to +10000, ±(75 ppm CO_2 + 3% of measured value) 0 to +120°C, Class 1 0 to +5ms^{-1}, ±(0.03ms^{-1} to 4% of measured value)
TSI 8533 Dust Trak Aerosol Monitor	$PM_{2.5}$ PM_{10}	Particle size range 0.1 to 15μm Resolution ±0.1% of reading or 0.001 mg/m^3 (whichever is greater)

Table S2 Observed outdoor meteorological conditions study the monitoring period (February – December 2019) (Bureau of Meteorology)

School Term period	Month Season	*Outdoor Ta (°C)*			*Outdoor RH%*		
		Ave 9am/3pm	**Min 9am/3pm**	**Max 9am/3pm**	**Ave 9am/3pm**	**Min 9am/3pm**	**Max 9am/3pm**
Term 1 14 Feb – 5 April 2019 (Summer-Autumn)	February	19.2/24	13.7/17	28.5/37	64/49	35/20	86/71
	March	18.2/23	9.5/15	29.6/37	66/49	32/18	96/84
	April	15.9/21	9.4/14	26.5/30	64/47	32/22	87/76
Term 2 23 April – 28 June 2019 (Autumn-Winter)							
	May	13.3/17	8.5/8	20.2/23	72/57	46/38	100/80
	June	10.3/14.5	4.5/9	15.6/19.1	80/63	61/45	100/91
Term 3 15 July – 20 Sept 2019 (Winter-Spring)	July	10.2/14.1	6/11.4	12.4/18.6	77/60	60/45	98/85
	August	10/13.3	6.4/7.9	16.4/17.6	71/58	42/43	90/94
	September	12.4/15.9	8.7/10.5	21.6/25.5	66/54	41/36	87/88
Term 4 7 Oct -19 Dec 2019 (Spring-Summer)	October	14.4/19.1	10/12.1	25.7/32.6	64/49	27/13	94/79
	November	15.7/19.8	10.5/12.9	32.3/33.4	63/49	17/21	94/98
	December	17.5/22.8	11.5/13.7	33.1/41.3	49/63	13/27	75/87

Table S3 Indoor air quality parameters of school classrooms for four (4) school terms during school hours (9:00am-3:30pm)

Classroom	*n*	T_a (°C)				*RH*%				CO_2 concentration levels				Term Period
		Ave	Std dev	Min	Max	Ave	Std dev	Min	Max	Ave	Std dev	Min	Max	
Term 1														
S1A	1178	22.0	2.84	12.6	31.4	55	8.23	34	80	1331	694.0	417	4064	5 February – 5 April (Summer-Autumn)
S1B	989	23.1	2.99	12.7	32.8	55	8.44	38	78	1323	642.5	412	4216	
S2A	433	21.8	2.55	13.6	28.6	54	6.73	32	77	1319	731.2	372	S2A	15 March – 5 April (Summer-Autumn)
S2B	433	22.2	2.54	14.7	28.3	52	7.37	31	68	882	403.5	332	2893	
S3A	1161	23.0	1.29	17.4	26.4	53	7.39	32	77	912	320.9	303	1856	6 March – 5 April (Summer-Autumn)
S3B	1161	23.5	1.72	19.3	28.3	51	8.04	31	70	925	308.3	362	1800	
S4A	972	22.7	1.70	15.9	25.9	53	6.12	37	67	1943	956.1	309	4204	14 February – 5 April (Summer-Autumn)
S4B	972	23.4	1.89	17.3	28.3	50	6.54	33	68	1843	900.2	331	4588	
S5A	783	23.8	2.10	16.8	30.2	51	9.83	28	79	980	467.2	386	3052	25 February – 5 April (Summer-Autumn)
S5B	783	23.1	1.89	15.7	30.0	51	8.52	31	79	1019	454.6	365	2539	
Term 2														
S1A	1068	19.2	2.58	10.3	24.9	63	5.67	47	78	1518	799.8	420	3735	23 April – 28 June (Autumn-Winter)
S1B	1231	19.7	3.38	5.9	27.1	61	5.77	44	80	1415	719.2	409	4110	
S2A	1320	19.4	2.31	10.0	24.1	60	5.39	41	73	1649	706.3	400	3710	
S2B	1320	18.9	2.11	11.9	23.4	57.2	6.10	43.3	71.4	1035	498.6	399	2983	
S3A	1203	20.3	2.39	13.7	25.7	57	6.04	37	70	1015	277.6	413	1917	
S3B	1203	20.2	2.12	14.2	24.9	55	5.92	41	73	958	281.6	390	1769	
S4A	1323	20.3	2.20	12.6	25.5	61	4.43	47	72	2177	1029.2	344	5000	
S4B	1323	21.0	2.16	12.8	26.2	57	4.57	40	71	1855	917.6	258	4578	
S5A	1461	20.7	2.19	15.7	25.2	51	8.27	34	70	827	506.9	389	3100	
S5B	1461	20.6	2.09	15.5	24.4	51	8.29	34	69	784	461.3	358	2860	

Classroom	N	T_a (°C)				RH%				CO_2 concentration levels				Term Period
		Ave	Std dev	Min	Max	Ave	Std dev	Min	Max	Ave	Std dev	Min	Max	
Term 3														
S1A	1350	18.7	2.52	8.6	25.5	61	6.15	42	79	1636	726.8	469	3799	15 July – 20 September (Winter-Spring)
S1B	802	19.1	2.87	8.9	23.9	60	5.39	43	77	1508	575.5	475	3033	
S2A	1336	19.1	2.47	10.2	24.6	56	6.85	38	74	1471	623.0	421	3164	
S2B	1336	18.8	2.23	12.2	23.9	54	5.43	41	71	1247	502.1	409	2713	
S3A	1324	18.8	1.22	14.2	22.1	56	4.63	44	68	1069	270.1	390	1784	
S3B	1324	19.8	1.74	13.4	24.4	52	5.44	38	74	977	286.1	286	1868	
S4A	1350	19.9	1.90	13.9	24.4	58	4.50	46	72	2235	915.2	419	4935	
S4B	1350	20.8	2.11	13.0	25.6	54	4.50	43	68	1676	637.3	377	3415	
S5A	108*	20.9	0.99	16.4	22.3	50	4.47	41	64	671	377.4	381	2081	
S5B	1350	21.1	1.27	16.0	25.5	44	6.58	29	63	657	347.4	333	2533	
Term 4														
S1A	540	20.1	2.93	12.8	28.3	56	6.29	40	71	1443	726.6	434	3955	7 October -19 December (Spring-Summer)
S1B	108*	23.3	2.81	16.2	28.5	49	4.35	38	59	1455	619.7	441	2844	
S2A	1417	20.5	2.35	12.6	28.7	53	5.89	32	68	1454	645.4	401	3789	
S2B	1417	20.4	2.42	13.8	30.0	50	6.26	29	65	1026	407.7	421	3013	
S3A	1454	21.1	1.54	16.5	24.0	53	4.66	37	65	1179	331.9	463	2060	
S3B	1454	22.3	2.24	16.3	29.6	49	6.13	26	64	945	302.7	426	1804	
S4A	1440	21.1	2.36	13.4	28.0	53	5.29	34	64	1648	862.9	395	4897	
S4B	1400	21.7	2.67	13.0	31.2	51	6.27	28	62	1519	708.3	397	3696	
S5A	680	21.8	2.88	15.5	28.2	48	7.97	28	63	970	452.1	191	2564	
S5B	1148	21.0	1.92	15.0	25.8	50	6.73	31	68	829	372.7	376	2301	

*monitored for four schooldays only

Table S4 Indoor condition parameters and student performance

	20 min average measurement							One day average measurement						
	Ta	**RH%**	**CO_2**	**Air velocity (ms^{-1})**	**MRT**	**$PM_{2.5}$**	**PM_{10}**	**Ta**	**RH%**	**CO_2**	**Air velocity (ms^{-1})**	**MRT**	**$PM_{2.5}$**	**PM_{10}**
TN	-.228**	**.289****	.097	.120*	**-.273****	**-.310****	-.153**	-.103	**.238****	-.105	-.190**	**-.240****	**-.270****	-.128*
E1	-.045	.092	.090	-.057	-.058	-.046	.023	-.042	.081	.021	-.096	-.057	-.029	.007
E2	-.088	.114*	-.004	-.046	-.016	-.046	-.014	-.068	.122*	-.025	-.091	-.013	-.025	-.005
CP	-.155**	.185**	.084	.123*	**-.232****	**-.249****	-.137*	-.046	.138*	-.077	-.116*	**-.203****	**-.225****	-.110*

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table S5 Stepwise regression analysis – 20 min average measurement and TN

Model	**R**	**R^2**	**Std. Error**	**R^2 change**	**Change Statistics**			
					F change	**df1**	**df2**	**Sig. F change**
1[a]	.310	.096	90.130	.096	35.478	1	333	.000
2[b]	.365	.133	88.412	.037	14.062	1	332	.000
3[c]	.387	.150	87.675	.017	6.607	1	331	.011
4[d]	.401	.161	87.235	.011	4.350	1	330	.038

a. Predictors: (constant), PM2.5
b. Predictors: (constant), PM2.5, MRT
c. Predictors: (constant), PM2.5, MRT, RH
d. Predictors: (constant), PM2.5, MRT, RH, Air velocity
e. Dependent variable: TN

Part 9: Appendices

RMIT Human Research Ethics Approval, CHEAN B 21563-06/18, 20 July 2018 (2 pages)

Victorian Department of Education and Training (DET), 2018-003781, 17 August 2018 (2 pages)

Available on request:
Amcosh Pty Ltd, Airborne Microbial Sampling at Various School and Aged-Care Facilities Report, December 2019 (48 pages)

Publications, engagement and media:

RMIT Media Release: *A breath of fresh air for vulnerable Australians*, 26 March 2019.

Podcast: *Air of mystery: ventilation quality and its impact on aged care facilities*, 8 April 2019.

Andamon, M.M.,Rajagopalan, P.,Woo, J.,Huang, R. (2019). *An investigation of indoor air quality in school classrooms in Victoria, Australia.* In: Proceedings of the 53rd International Conference of the Architectural Science Association (ANZAScA), IIT Roorkee, India, 28-30 November 2019.

Citations in:
Poor ventilation may be adding to nursing homes' COVID-19 risks
by Geoff Hanmer (University of Adelaide) and Bruce Milthorpe (University of Technology Sydney):
The Conversation, 20 August 2020
UTS, 20 August 2020
Architecture and Design, 21 August 2020
ArchitectureAU, 31 August 2020
HelloCare, 31 August 2020

Under peer-review with Indoor Air Journal (November 2020):
Rajagopalan, P., Andamon, M.M., and Woo, J. *Examining the indoor air quality, ventilation rates and student attention in school classrooms in Victoria, Australia*

College Human Ethics Advisory Network (CHEAN)
College of Design and Social Context
NH&MRC Code: EC00237

Notice of Approval

Date:	**20 July 2018**
Project number:	**CHEAN B 21563-06/18**
Project title:	**‘Enhanced Indoor Air Quality in Schools and Aged Care Centres’**
Risk classification:	**Low risk**
Chief investigator:	**Associate professor Priyadarsini Rajagopalan**
Status:	**Approved**
Approval period:	From: **20 July 2018** To: **30 June 2020**

The following documents have been reviewed and approved:

Title	Version	Date
Risk Assessment and Application Form	2	27 June 2018
Participant Information Sheet and Consent Form (School Teachers)	2	27 June 2018
Participant Information Sheet and Consent Form (Parents)	3	20 July 2018
Participant Information Sheet and Consent Form (Aged Care Staff and Residents)	2	27 June 2018
Recruitment Email (School Principals)	1	27 June 2018
Recruitment Email (Aged Care Centres)	1	27 June 2018
Recruitment Flyer (Schools)	1	27 June 2018
Recruitment Flyer (Aged Care Centres)	1	27 June 2018
Recruitment Flyer (Parents)	1	20 July 2018
Indoor Conditions Survey (Schools)	2	20 July 2018
Indoor Conditions Survey (Aged Care Centres)	2	20 July 2018
Test of Attention	1	27 June 2018
Email from Department of Education and Training	1	20 July 2018
Email from Aged Care Centre	1	20 July 2018
Air Ventilator Installation, Operation, and Service Manual	1	20 July 2018
Ventilator Leaflet	1	20 July 2018
Summary of Literature	1	20 July 2018
Response to CHEAN	1	20 July 2018

The above application has been approved by the RMIT University CHEAN as it meets the requirements of the *National Statement on Ethical Conduct in Human Research* (NH&MRC, 2007).

Terms of approval:

1. **Responsibilities of chief investigator**
   It is the responsibility of the above chief investigator to ensure that all other investigators and staff on a project are aware of the terms of approval and to ensure that the project is conducted as approved by CHEAN. Approval is valid only whilst the chief investigator holds a position at RMIT University.
2. **Amendments**
   Approval must be sought from CHEAN to amend any aspect of a project. To apply for an amendment use the request for amendment form, which is available on the HREC website and submitted to the CHEAN secretary. Amendments must not be implemented without first gaining approval from CHEAN.

3. **Adverse events**
   You should notify the CHEAN immediately (within 24 hours) of any serious or unanticipated adverse effects of their research on participants, and unforeseen events that might affect the ethical acceptability of the project.
4. **Annual reports**
   Continued approval of this project is dependent on the submission of an annual report. Annual reports must be submitted by the anniversary of approval of the project for each full year of the project. If the project is of less than 12 months duration then a final report only is required.
5. **Final report**
   A final report must be provided within six months of the end of the project. CHEAN must be notified if the project is discontinued before the expected date of completion.
6. **Monitoring**
   Projects may be subject to an audit or any other form of monitoring by the CHEAN at any time.
7. **Retention and storage of data**
   The investigator is responsible for the storage and retention of original data according to the requirements of the *Australian Code for the Responsible Conduct of Research* (section 2) and relevant RMIT policies.
8. **Special conditions of approval**
   Nil.

In any future correspondence please quote the project number and project title above.

Dr Marsha Berry
Chairperson, College Human Ethics Advisory Network (CHEAN B)
RMIT University

Dr Scott Mayson
Deputy Chairperson, College Human Ethics Advisory Network (CHEAN A)
RMIT University

cc: Dr David Blades (CHEAN secretary), Dr Mary Myla Andamon, Dr Jin Woo.

Department of
Education & Training

2 Treasury Place
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Telephone: 03 9637 2000
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2018_003781

Dr Mary Andamon
School of Property, Construction and Project Management
Building 8, Level 8
124 La Trobe Street
MELBOURNE 3000

Dear Dr Andamon

Thank you for your application of 29 June 2018 in which you request permission to conduct research in Victorian government schools titled *Enhanced Indoor Air Quality (IAQ) for Improving the Well-being of Vulnerable Population in Victoria.*

I am pleased to advise that on the basis of the information you have provided your research proposal is approved in principle subject to the conditions detailed below.

1. Department approved research projects currently undergoing a Human Research Ethics Committee (HREC) review are required to provide the Department with evidence of the HREC approval once complete.

2. The research is conducted in accordance with the final documentation you provided to the Department of Education and Training.

3. Separate approval for the research needs to be sought from school principals. This is to be supported by the Department of Education and Training approved documentation and, if applicable, the letter of approval from a relevant and formally constituted Human Research Ethics Committee.

4. The project is commenced within 12 months of this approval letter and any extensions or variations to your study, including those requested by an ethics committee must be submitted to the Department of Education and Training for its consideration before you proceed.

5. As a matter of courtesy, you advise the relevant Regional Director of the schools that you intend to approach. An outline of your research and a copy of this letter should be provided to the Regional Director or governing body.

6. You acknowledge the support of the Department of Education Training in any publications arising from the research.

7. The Research Agreement conditions, which include the reporting requirements at the conclusion of your study, are upheld. A reminder will be sent for reports not submitted by the study's indicative completion date.

I wish you well with your research. Should you have further questions on this matter, please contact Youla Michaels, Project Support Officer, Insights and Evidence Branch, by telephone on (03) 7022 0306 or by email at michaels.youla.y@edumail.vic.gov.au.

Yours sincerely

Zoran Endekov
Senior Research Officer
Insights and Evidence

17/08/2018

VICTORIA State Government

Part 10: Acknowledgements

The authors acknowledge the Virtual Centre for Climate Change Innovation (VCCCI) of the Victorian Department of Environment, Land, Water and Planning (DELWP) who funded the Victorian Climate Change Innovation Grant project '*Enhanced Indoor Air Quality (IAQ) for Improving the Well-being of Vulnerable Population in Victoria*' (2018-2020).

We express our gratitude to the school principals, school administration and facility management personnel of the participating schools in Melbourne and Geelong and to the portfolio and facility management of Regis Aged Care, Vasey RSL Care and Multicultural Aged Care Services (MACS). Our sincere appreciation particularly goes to Dr Kaushik Sridhar (Regis Aged Care), Mr Chris Gray (Vasey RSL Care) and Mr Alwin Gallina (MACS) for their great cooperation that enabled us to conduct the study.

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Part 11: References

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