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Determination of Locations of High Concentration of Indoor Air Pollutants Using Air Flow Measurements and Modelling

Kit Orven Malbas, Ma. Kevina Alfonso, Ren Paulo Estaquio, Joshua Agar, Julius Rhoan Lustro, Job Immanuel Encarnacion, Joseph Gerard T. Reyes*

University of the Philippines Diliman, Quezon City, 1101, Philippines
jtreyes2@up.edu.ph

Sick Building Syndrome (SBS) is a malady experienced by occupants after prolonged exposure to various indoor air pollutants that are resident in enclosed spaces. Often, these indoor air pollutants are hardly detectable by normal human senses, and occupants are unaware of their exposure. In places of work, people suffering from SBS tend to become less productive. There is an economic impact brought about by this malady. One form of intervention is to install indoor air pollution monitors in enclosed areas with a significant number of occupants who spend considerable time in these facilities. These monitors are usually installed in locations that are suspected to have high concentrations of indoor air pollutants, and the number of units installed may vary according to considerations such as room size, the number of suspected areas of high pollutant concentrations, and layouts of room fixtures and furnishings. Since sophisticated monitoring systems may be expensive, there are limitations in the number of units that can be deployed. Identification of areas with high pollutant concentration in an enclosed facility allows for an optimal number of monitors to be deployed. Airflow and CO_2 measurements were taken in two different indoor sites. The results of the measurement will be used as input in future simulations that will be employed to optimize the distribution of sensors. The center of a room is determined to be a zero-velocity region which poses a challenge in future simulations, while additional measurement runs with greater than 3 occupants are recommended since the resulting CO_2 concentration of 478 ppm is more similar to the ambient concentration, which indicates the negligible contribution of the CO_2 sources, and a challenge in simulation.

1. Introduction

Indoor air quality (IAQ) is a critical issue for human comfort and health, especially since people spend most of their time indoors, increasing the risk of exposure to pollutants that originate from both indoor and outdoor sources. These pollutants may remain undetected because they are invisible and cannot be smelled or tasted. The contaminants can contribute to various health problems that range from mild irritations to severe ailments depending on the level and type of exposure. Exposure may lead to Sick Building Syndrome (SBS) and Building Related Illnesses. These are two categories of ailments where SBS involves symptoms such as lethargy or fatigue, headache, dizziness, and irritation of mucous membranes while Building Related Illnesses are diagnosable illnesses that can be attributed directly to specific airborne building contaminants (US EPA, 2015). The risks associated with exposure to indoor air pollutants extend beyond human health; they can also affect building owners and organizations that operate in the building.

Indoor air pollutants (IAP) come from various sources, including outdoor air infiltration, cigarette smoking, cooking, personal activities, and dusting of indoor areas. Building location and air intake, building design, building materials and furnishings, and indoor activities all contribute to the degree of IAP infiltration.

In Europe, indoor air quality is a key component for building assessment, and standards have been established to address IAQ, thermal environment, lighting, and acoustics (Asadi et al., 2011). Locally, the Department of Labor and Employment (DOLE) has listed more than 400 indoor air contaminants and their respective threshold limits in the Occupational Safety and Health Standards (DOLE, 2013). Indoor air pollution could result from Indoor air quality monitoring has become a necessity to safeguard the health of occupants of indoor facilities

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from the risks of indoor airborne contaminants. Detection of these contaminants in significant quantities provides a key first step. IAQ monitoring employs different technologies, such as gas sensing, sensor networks, data processing, and decision mechanisms. Monitoring stations that contain several sensors, each dedicated to detecting and measuring a particular contaminant can be set up in strategic locations. Real-time measurements can be performed, and all recorded data can be sent to stakeholders with onsite and offsite access.

The design of IAQ monitoring systems includes consideration of the type of sensors and their positions, control interface, analysis, etc. It is easy to select the most sophisticated sensors and deploy them in numbers. However, this is impractical due to the high cost of the sensors and system. Low-cost sensor networks that allow for real-time IAQ monitoring are being developed, but a need to optimize distribution is still needed to ensure that cost is minimized, including operational and maintenance cost that increases as more and more sensors are deployed. An example of a low-cost sensor network is the Raspberry Pi (RPi) implementation of a multi-pollutant sensing system by Zhang et al. (2021). The sensors measured $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3, CO_2, and other volatile compounds. The RPi implementation allowed real-time monitoring and the capability to store data in the cloud. However, all installations only included a single sensor for each pollutant resulting in the non-identification of the distribution of pollutants within an area.

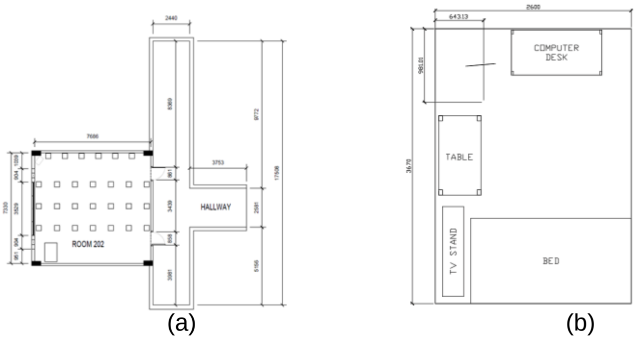
Coleman and Meggers (2018) developed a low-cost distributed sensor system that can gather data about the temporal and spatial distribution of IAPs (CO_2, VOCs, O_3, NO_2) within an office setting. Large concentrations were found to be highest at desk height, which correlates with the spatial occupancy of the office. However, the authors indicated that the positions of the sensors were, at best, an inference of where such sensors should be placed. Lotrecchiano et al. (2021) applied spatial interpolation techniques to calculate missing outdoor air quality data due to traffic constraints. This an also be done for an indoor environment, although computational fluid dynamics (CFD) may be employed at this time since installation in a room can be more flexible.

Mou et al. (2022) used CFD to model the airflow inside a 91-seater 210 m^2 air-conditioned seminar room. This was done to locate the optimum placement of CO_2 sensors that would accurately measure CO_2 concentration in an indoor setting. The best positions determined for the sensors are within the vicinity of the ceiling where the air is fully mixed. However, it is unclear whether physical sensors will reflect the same result, as no information on physical sensor installation was provided.

The study then aims to determine the optimal distribution of sensors in an indoor setting, specifically set to mimic local working conditions in the Philippines. The current work revolves around flow measurement and collection of carbon dioxide concentration to fully characterize the spatial and temporal distribution of an indoor location. The gathered data will be in aid of simulation where distribution optimization will be performed, leading to an accurate design of sensor networks.

2. Methodology

Two pilot sites are used in this study: a classroom, primarily used for filtration and ventilation testing, and a bedroom of a typical office worker. The classroom emulates in-use working conditions during a typical office day, while the bedroom emulates in-use conditions during the night/resting time. The measurements will then be used as reference values for simulation, leading to the distribution optimization of IAQ monitoring sensors.



(a) (b)

Figure 1: Sites for testing: classroom (a) and bedroom (b)

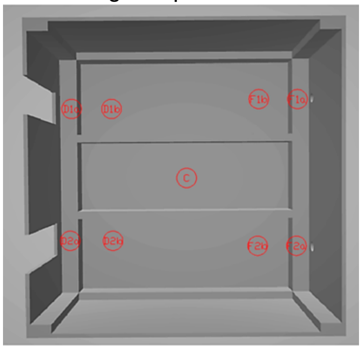
The classroom is a 7,696 mm x 7,330 mm x 3,083 mm enclosed space with 2 wall-mounted exhaust fans at an assumed max capacity of 2,543 CFM. An exterior south-facing wall is exposed to ambient conditions, while all three remaining walls are interior to the building. All measurements within the classroom are done without only one occupant – the person measuring flow. This is to determine base flow conditions within the room.

The bedroom is a 3,670 mm x 2,600 mm x 2,400 mm space with a single closed window, with its center 1,400 m away from the north wall. A single standard commercial stand fan is used for ventilation. There are two exterior walls facing the east and south. Airflow measurements are taken similarly to the method applied to the classroom conditions, although carbon dioxide measurements are taken with one sleeping occupant, with a presumable basal CO_2 emission rate of 11.0 L/h (Sakamoto et al., 2021).

2.1 Flow measurements

An Extech SDL350 Hotwire anemometer with a velocity measurement range of 0.2 - 25 m/s and temperature measurement range of 0 - 50 °C was used to obtain flow measurements. Airflow within each site is determined by obtaining flow measurements on Identified points.

Figure 2 shows the identified points for the classroom site. The points were determined by identifying sources of forced and induced draft within the room following the findings of Hanzawa et al. (1987) on draft as one of the leading complaints in indoor ventilation of closed spaces.



D1a – Door 1 Slit. 5 cm away from door at floor level
D1b – Door 1 Slit. 0.5 m away from door at floor level
D2a – Door 2 Slit. 5 cm away from door at flow level
D2b – Door 2 Slit. 0.5 m away from door at floor level
C – Center of room. 1.6 m height. No airflow in this measuring point
F1a – Exhaust Fan 1. 2.5 cm away fan face at center of the face.
F1a – Exhaust Fan 1. 15 cm away fan face at center of the face.
F1a – Exhaust Fan 2. 2.5 cm away fan face at center of the face.
F1a – Exhaust Fan 2. 15 cm away fan face at center of the face.

Figure 2: Identified points for flow measurement in the classroom test site

Figure 3 shows the identified points for the bedroom. The points are made to be as distributed as possible while also accounting for points directly in front of the fan. All measurements are done at a height of 1.2 m.

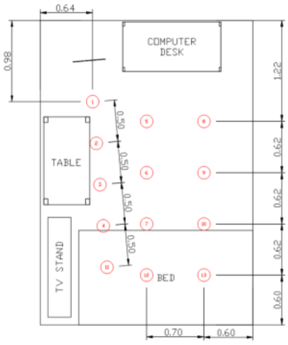
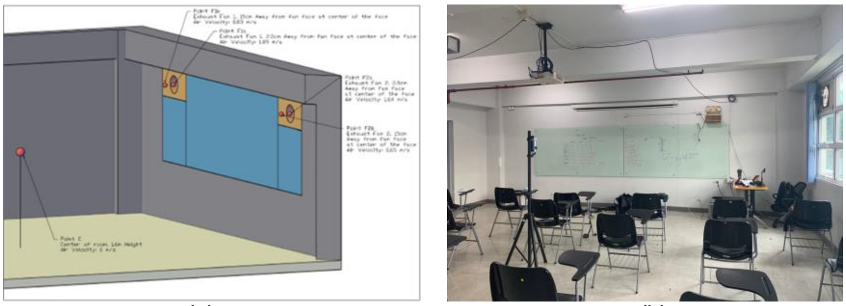


Figure 3: Identified points for flow measurement in the bedroom test site

2.2 Carbon dioxide concentration



(a) (b)

Figure 4: Model of the classroom with identified point C (a) and actual classroom with sensor (b)

An Aeroqual series 500 IAQ monitor with a minimum detection limit of 20 ppm, accuracy of $\pm$ 20 ppm, and resolution of 1 ppm at an operating range of 0 - 40^{o} C was used for CO_2 measurements. Carbon Dioxide measurement for the classroom was only done for a single point – the center of the room. This emulates how CO_2 accumulates within an enclosed ventilated space. The CO_2 sensor is set up as in Figures 4b and 4d at a height of 1.6 m. The room was occupied by three people identified as sources of CO_2 for this study. Both ventilation fans were made to run at full capacity. Measurements were taken for 60 min.

Figure 5: Model of the bedroom with identified points (a) and actual bedroom with sensor (b)

Carbon Dioxide measurement for the bedroom was done at three points, as in Figure 5a. Each CO_2 measurement was done on different days, all at times when the occupant was asleep. Points 1 and 3, similar to the classroom situation, are areas where CO_2 accumulates. However, points 1 and 3 differ in height, with point 1 at 0.83 m from the floor, nearer to the height of the bed, and point 3 at 2.3 m, which is near the ceiling. Point 2 is situated near the window and is intended to identify whether there is a contribution from the window even when it is closed.

3. Results

3.1 Flow measurements

Table 1: Flow measurements for each point in the classroom test site

Measurement Point	Sampling Duration (min)	Sampling Interval (Hz)	Average Inflow (m/s)	Standard Deviation (m/s)	Average Air temperature (°C)	Standard Deviation (°C)
D1A	10:00	0.50	3.52	0.13	26.7	0.1
D1B	10:00	0.50	0.63	0.06	28.0	0.1
D2A	5:00	-	4.82	0.06	-	-
D2B	5:00	0.50	0.99	0.07	27.7	0.0
F1A	5:00	1.00	1.89	0.04	29.9	0.1
F1B	5:00	1.00	0.83	0.04	30.0	0.0
F2A	5:00	1.00	1.64	0.03	30.3	0.1
F2B	5:00	1.00	0.65	0.04	30.4	0.1
C	5:00	1.00	0.00	-	31.1	0.2

Table 2: Flow measurements for each point in the bedroom test site

Measurement Point	Measurement Duration (min)	Reading 1 (m/s)	Reading 2 (m/s)	Average Inflow (m/s)
1	2:00	2.27	2.37	2.35
2	2:00	2.6	2.57	2.44
3	2:00	2.39	2.08	2.25
4	2:00	2.09	1.9	2.04
5	2:00	0.32	0.43	0.27
6	2:00	0.17	0.26	0.31
7	2:00	0.47	0.37	0.55
8	2:00	0.01	0.37	0.2
9	2:00	0.15	0.26	0.25
10	2:00	0.21	0.36	0.24
11	2:00	1.5	1.52	1.53
12	2:00	0.86	0.89	0.73
13	2:00	0.11	0.11	0.17

For the classroom, the inflow values from the door (D1A, D1B, D2A, D2B) do not match the flow going out of the room provided by the exhaust fans (F1A, F1B, F2A, F2B). This mismatch may be purely due to the measurement that provides the velocity of air rather than the mass flow of the air – the area of the slit under the door is smaller than the projected area of the fan. This finding is consistent with Hanzawa et al. (1987) that an enclosed room leads to an accumulation of pollutants if only two exhaust fans are used.

There is no measurable airflow in Point C (center of the room). This presents a problem for simulations since convergence is hard to achieve with low or zero airflow values. It is then recommended to add air circulation equipment, such as a standard stand fan, to introduce more airflow into the space. However, this also indicates that CO_2 may accumulate at this point and be used for CO_2 measurement, as stated in the methodology.

For the bedroom, it is observed that points 1, 2, 3, 4, and 11 have the highest velocity magnitudes. This is expected since these points lie within the presumed velocity vector of the air pushed by the fan. Points 5 and 9 are observed to be the area with the least amount of air circulation. Similar to the classroom, this area is then designated as an area of accumulation of CO_2.

3.2 Carbon dioxide concentration

Initial room Carbon Dioxide concentration starts at 534 ppm, although this might be due to the researchers being near the Carbon Dioxide sensor at the beginning of data logging. The concentration is observed to stabilize at an average value of 478 ppm after 30 min. This is well below the threshold limit set by DOLE of 5,000 ppm (DOLE, 2013) and below the consensus of a 1,000 ppm threshold (Lowther et al., 2021). In comparison, the base CO_2 concentration for a typical outdoor environment is 421 ppm. It is suspected that three occupants may not have a significant impact on the CO_2 and may not be enough to emulate full-working conditions. It is recommended to have at least 15 participants to characterize full-working conditions. At this point, contrary to the discussion on the accumulation of CO_2 due to the zero-velocity magnitude at point C, it seems that two exhaust fans are enough for ventilation.

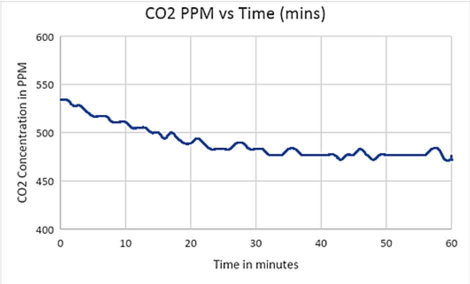


Figure 6: CO_2 concentration in the classroom test site for 60 min

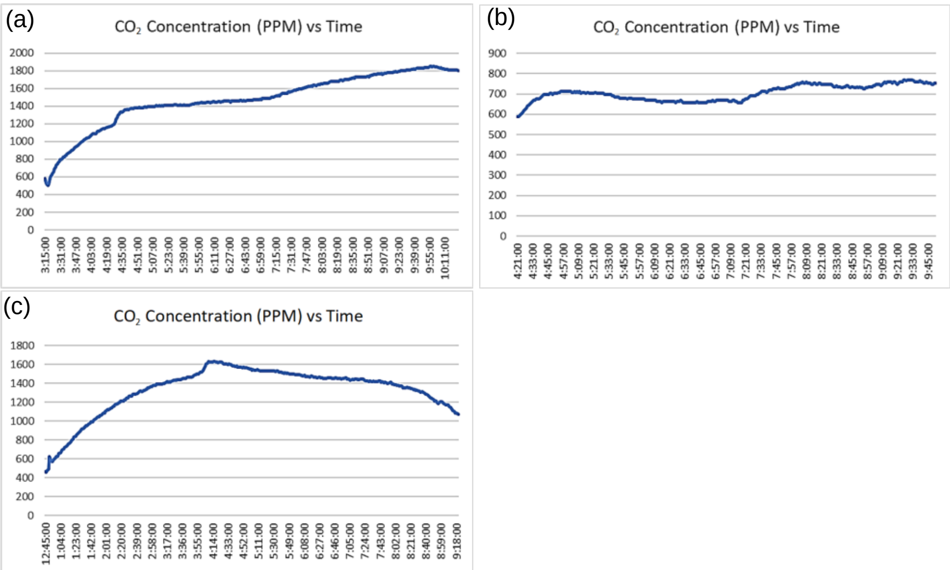


Figure 7: CO_2 concentrations for point 1 (a), point 3 (b), and point 2 (c)

Figures 7a and 7b show the CO_2 concentration at points 1 and 3, 0.83 and 2.3m from the floor. Steady-state values were not observed in point 1 (level of the bed). This is the level of the CO_2 source – without fresh air intake, and where CO_2 continues to accumulate well past the 1,000 ppm threshold. This follows the expected trend of accumulation and is identified as possibly detrimental to occupational health. However, The CO_2 concentration near the ceiling remains to be relatively steady at low values indicating non-accumulation.
An unexpected trend is observed at point 2 (Figure 7c), where CO_2 concentration increases as expected but decreases at about 4 AM in the morning. Since the measurement devices are unattended while the occupant is asleep and no other recording device is present, it is impossible to ascertain the source of the drop in the concentration. An inference can be made about the contribution of the window – the difference in the thermal resistance of the window and the wall resulted in a non-negligible heat transfer leading to circulation within the vicinity of the window or ambient conditions on the testing for point 2 allowed for leakage of air. All inferences and observations from the flow and CO_2 measurements provide valuable information on future simulations to determine the optimal distribution of IAQ monitoring sensors within an indoor site.

4. Conclusion

Airflow and CO_2 measurements were obtained from two sites: a classroom to emulate an office setting and a bedroom to emulate an in-house setting used during resting time. Multiple points within each setting were identified to characterize airflow within each room. The airflow measurements for the classroom indicate the large influence of draft from minimal spaces, such as a door slit, on the circulation of air. The center of the room is identified to be a zero-velocity region when there is no forced ventilation inside the room. This may lead to challenges in simulation convergence, and it is recommended to have an additional ventilation element both in experiments and in simulations. A similar finding was observed in the bedroom site. Carbon dioxide accumulation was measured, and it was found that the current setup of the classroom with 3 occupants may not be enough to influence the CO_2 concentration since the resulting stable concentration of 478 ppm was well below the threshold of 1,000 ppm and very similar to ambient concentration at 421 ppm. Three distinct trends for CO_2 concentration were observed in the bedroom – one distinct trend for each point of measurement. It was found that CO_2 concentration on the ceiling does not vary while concentration at the level of the CO_2 source increases with prolonged exposure to the source. However, CO_2 concentration near the window increases and then drops without certainty on the cause of the drop. This may be further studied and included in future simulations and added as consideration on the distribution optimization of IAQ monitoring sensors.

Acknowledgments

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