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# Sensor Location Methodology for Improved IEQ Monitoring in Working Environments

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## ABSTRACT

*In the current era, sensors in buildings have become an essential requirement for wide applications such as monitoring indoor air quality (IAQ), thermal and environmental conditions, controlling building heating, ventilation, and air-conditioning systems (HVAC). To accurately control the IAQ for all areas in the indoor space, it is necessary to obtain considerable data from different locations in the space for more precision. The airflow in a room is not uniform, which raises the question of where the environmental sensor should be positioned with regard to optimum performance of IAQ and thermal comfort. This paper uses a case study of an open-plan office in Loughborough, UK, to assess the indoor climate conditions from real-time measurements from several sensors placed in different locations in the office and investigates the potency of using ventilation effectiveness (Ez), one of the IAQ relative indicators, as a preference to locate environmental sensors. The air parameters measured by the sensors are indoor temperature ($t_a$), relative humidity (RH), carbon dioxide ($CO_2$), total volatile organic compounds (tVOCs), formaldehyde ($CH_2O$) and particulate matter ($PM_{2.5}$ and $PM_{10}$). Computational fluid dynamics (CFD) simulations were conducted to identify the areas in the office with low Ez evaluated using the age-of-air. Results showed that the measurement of RH and $CO_2$ levels were marginally different between the sensors. A larger difference was found for temperature, assuming local heat sources significantly influenced the measured temperatures. Also, the calculated Ez from the measured data of each sensor was found to be different for each sensor location. The results from field measurements and CFD simulations can support decision making regarding the position of environmental sensors and the collection of indoor climate data in open-plan offices.*

## INTRODUCTION

Indoor Air Quality (IAQ) is one of the essential aspects of healthy buildings as people spend most of their lifetime indoors. It directly impacts their health (WHO, 2015), well-being and productivity (Wyon, 2005). The COVID-19 pandemic highlighted the need for better IAQ. Achieving an acceptable IAQ has become an essential design objective for newly constructed and renovated buildings as well as for the operational system in existing buildings. IAQ can be measured by the absolute value of contaminant/pollutant concentration (Yang et al. 2009) and can be measured by relative indicators such as

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ventilation effectiveness (Zhuang, Li and Tu, 2014) and age-of-air (Buratti et al., 2011).

The absolute value of the pollutant concentration could be obtained using environmental sensors. With the continual development of low-cost sensor technology (Kumar *et al.*, 2018; Morawska *et al.*, 2018; Saini *et al.*, 2020), it has become much more feasible for environmental sensors to be used in different indoor sectors.

The relative indicators for IAQ tell how fresh the indoor air in a breathing zone can be measured by ventilation effectiveness (Ez). Ez is an indicator of the quality of supply air distribution in ventilated rooms. It represents how well a considered space is ventilated compared to a perfect air mixing condition (Rim and Novoselac, 2010). The effectiveness of ventilation in relation to pollution control in an occupied space is mostly evaluated using the age-of-air (Rim and Novoselac, 2010). Age-of-air is defined as the time for air particles from entering the room to reach a certain point in the indoor (Yang et al., 2014). The local value of age-of-air in a specific location describes the freshness of the air and is directly correlated with the airflow path (Rim and Novoselac, 2010). The shorter the age-of-air, the fresher the air due to higher air update frequency. Vice versa, the longer the age-of-air indicates that the air dredge is not free, and the air is stale. Therefore, the age of air is the most direct parameter to reflect the fresh degree of indoor air (Yang et al., 2014). The age-of-air equation is described in Chao and Wan, (2004).

To accurately control the IAQ for all areas in the indoor space, it is necessary to obtain considerable data from different locations in the space for more precision. The airflow in a room is not uniform, which raises the question of where a sensor should be positioned. The ideal location of the sensor depends on the intended purpose of the sensor. In other words, what is the reason for using the sensor? For instance, to detect a chemical and biological warfare (CBW) or transmission of infectious diseases (TID), the areas where the minimal amount of contamination needed to be sensed over a sensing period of time is the ideal location for the sensor to be placed (Fontanini et al., 2016). With regard to optimum performance of IAQ and thermal comfort, areas where maximum concentrations accumulate in breathing zones or areas with stagnate air are of interest to ensure the required ventilation rate is achieved. In some cases, the concentration of the pollutants in the enclosed environment does not reach the threshold limit value (TLV) due to having the air well mixed at the monitored location. The existing guidelines for indoor environmental sensor arrangement are useful yet generic, not giving enough consideration to critical variables (i.e., ventilation system and room layout) that could directly affect the airflow and pollutant distribution in the space and consequently influence IAQ.

The current work investigates the influence of the location of environmental sensors on its measurement and on controlling the indoor environment. The Ez was also evaluated using measured data and CFD simulations to identify the areas in the office with the shortest and longest age-of-air.

## METHODOLOGY

### Pollutants in an Office Environment

In real life, the indoor environment would have different sources of emissions depending on the space functionality. The emission sources in an indoor open-plan office are mainly from carpets, furniture, HVAC and people (CIBSE, 2020) and are primarily controlled by ventilation. Some of the key pollutants found in offices and their permissible criteria are listed in Table 1.

**Table 1. Permissible Criteria for IEQ parameters**

| Air Parameter | Acceptable comfort criteria | Source |
|---|---|---|
| ta | 22-24°C (71.6-39.2°F) | CIBSE Guide A |
| RH | 40-60 % | CIBSE Guide A |
| $CO_2$ | <1000 ppm | RESET Air v2 |
| $CH_2O$ | 0.1 mg/m$^3$ *(30-minute average concentration) | WHO Guidelines |
| tVOCs | <500 µg/m$^3$ | RESET Air |
| $PM_{2.5}$ | <35 µg/m$^3$ | RESET Air v2 |
| $PM_{10}$ | <50 µg/m$^3$ | WELL, v2 |

### Office Description

The open-plan office is located on the ground floor of a two-story building oriented southwest (with a degree angle of 208° relative to the north) in Loughborough, UK. The office building is located on a university campus and approaches a lawn landscape and a small parking lot. The area and the volume of the office are 148.5m$^2$ and 445.5m$^3$, respectively. The external façade of the office includes six windows of the same shape, type, and dimension. The office can accommodate up to 19 occupants. The type of activity work is sedentary office work. The open-plan office is mechanically ventilated with the supply and extract diffusers at ceiling level (mixing ventilation arrangement), as shown in Figure1.

### Real-time Measurements

The air parameters were measured using two types of monitors: HOBO MX1102 (Tempcon Instrumentation Ltd, 2022) and Airthinx IAQ (Airthinx, 2022). HOBO MX1102 measures $t_a$, RH, $CO_2$ concentration, and the dewpoint. Same air parameters are measured using the Airthinx IAQ monitor in addition to the levels of $CH_2O$ and tVOCs, $PM_{2.5}$ and $PM_{10}$. The tVOCs are measured with respect to ethanol. All monitors were mounted at a height of 1.5m. Figure 1 shows the location of each monitor in the open-plan office, each identified with a different colour. Monitors A1, A2 and A3 are HOBO MX1102. Monitor AX is the Airthinx IAQ.


**Figure 1** Examined open-plan office layout, including the occupant workplaces, HOBO MX1102 and Airthinx IAQ monitors, and supply and extract air diffusers at the ceiling level.

### CFD Simulation Inputs

The outdoor air rate was based on the floor area of the space as the number of occupancies was unknown during the monitored data. Therefore, in the CFD simulations, the number of occupancies varied to identify the areas in the open-plan office with stagnant air at different occupancy levels and different ventilation rates. The open-plan office was simulated under four scenarios, three scenarios with varying occupancy densities (0, 4 and 19) and one with the main office door open at full occupancy. The outdoor air requirement for the office with full occupancy was found to be 383.05 L/s. For every occupant in the simulation, a $CO_2$ generation rate was defined (0.0052 L/s), and a prescribed removal rate of 10 L/s/person was added as recommended by guidelines. The prescribed outdoor air supply rates are based on the metabolic pollutants of occupants according to their activity or to the size of the space. For sedentary office work, the minimum ventilation rate is 10 L/s per person for an office (CIBSE, 2015). The outdoor air supply per m$^2$ was set to 1.3 L/s (BSI, 1991). Thus, the rates at which the main air handler unit delivers outdoor air were proportional to the floor area. No windows are assumed to be opened, and no filters were added. Office equipment were also included in the simulation to reflect the real case scenario and was assigned to operate only during occupancy hours (08:00 to 18:00). The boundary conditions for the CFD were taken from the EnergyPlus simulation output of a typical winter working day at 11:00 am from a winter design week simulation. The turbulence model used was K-e, and the discretisation scheme used was power law.

## Data-analysis

The collected data was collated and statistically analysed using pandas, a software library written for the Python programming language for data manipulation and analysis (Pandas, 2018). Only data corresponding to working hours was processed. Preliminary analysis showed the indoor conditions of the open-plan office were within the comfort range for $t_a$, $CO_2$, $CH_2O$ $PM_{2.5}$ and $PM_{10}$. On the other hand, RH levels were below the comfort range for most of the measuring period. Besides, the tVOCs levels crossed the TLV, with a maximum value reached of 4.721667 ppm. It is noteworthy that the $CO_2$, $CH_2O$ and tVOCs levels follow a similar trend during occupational hours, indicating that the rise of levels for $CH_2O$ and tVOCs is also associated with the presence of occupants, which might be influenced by either the type of occupants' activities or by the changes of external weather conditions. Although the air quality at Loughborough UK is categorised as 'fair', meaning that the air quality is generally acceptable for most individuals. However, sensitive groups may experience minor to moderate symptoms from long-term exposure (Accuweather.com, 2021). The representative data of the air parameters in the results section are the sum of the hourly data for every sensor calculated from the 10 minutes interval recorded data.

Using the $CO_2$ measured data by all sensors, the zone air distribution effectiveness (Ez) was calculated from the measured data of the four monitors in accordance with ASHRAE standard 62.1-2019 (Equation 1). From the calculated Ez, the required ventilation rate for comfort and health were determined using Equations 2 and 3 (CIBSE KS17, 2011). The $CO_2$ concentrations were used for the calculations as it was the only pollutant measured by all monitors in the open-plan office. The definitions of the variables for each equation and their inputs are listed in Table 2.

$$E_z = \frac{(C_e - C_s)}{(C - C_s)} \tag{1}$$

$$Q_c = 10 \times \frac{G_c}{C_{c},i - C_{c},o} \times \frac{1}{\varepsilon_V} \tag{2}$$

$$Q_c = 10 \times \frac{G_c}{C_{c},i - C_{c},o} \times \frac{1}{\varepsilon_V} \tag{3}$$

**Table 2. Equations 1,2, and 3 Defined Variables and Inputs**

| $E_z$= zone air distribution effectiveness | | $Q_c$= the ventilation rate requires for comfort (L/s) | | $Q_h$= the ventilation rate required for health (L/s) | |
|---|---|---|---|---|---|
| Variables | Input | Variables | Input | Variables | Input |
| $C_e$= average pollution concentration at the exhaust (ppm) | 475 | $G_c$ = the sensory pollution load (olf) | 1 olf × 19 (BSI, 1991) | $G_h$ = the pollution load of a chemical (L/s) | 0.0052 × 19 |
| $C_s$= average pollution concentration at the supply (ppm) | 400 | $C_c,i$ = the desired perceived indoor air quality (decipol) | Category B: 1.4 (BSI, 1991) | $C_h,i$ = the guideline value of a chemical (ppm) | 1000 |
| $C_i$ = average pollution concentration at the breathing zone (ppm) | Measured $CO_2$ data | $C_c,o$ = the perceived outdoor air quality at air intake (decipol) | Excellent outdoor air quality (0 dp) (BSI, 1991) | $C_h,o$ = the outdoor concentration of a chemical at air intake (ppm) | 400 |
| | | $E_z$= the ventilation effectiveness (-) | | $E_z$ = the ventilation effectiveness (-) | |

## RESULTS & DISSCUSSION

Figure 2 reflects the differences in the distribution in the measured data and the unusual observations illustrated by the outliers in the form of boxplots. While in the cumulative frequency distribution graphs, the differences between sensors are smaller when data behaves in a similar pattern and plotted lines have a similar range. The graphs also highlight the comfort ranges in the space.

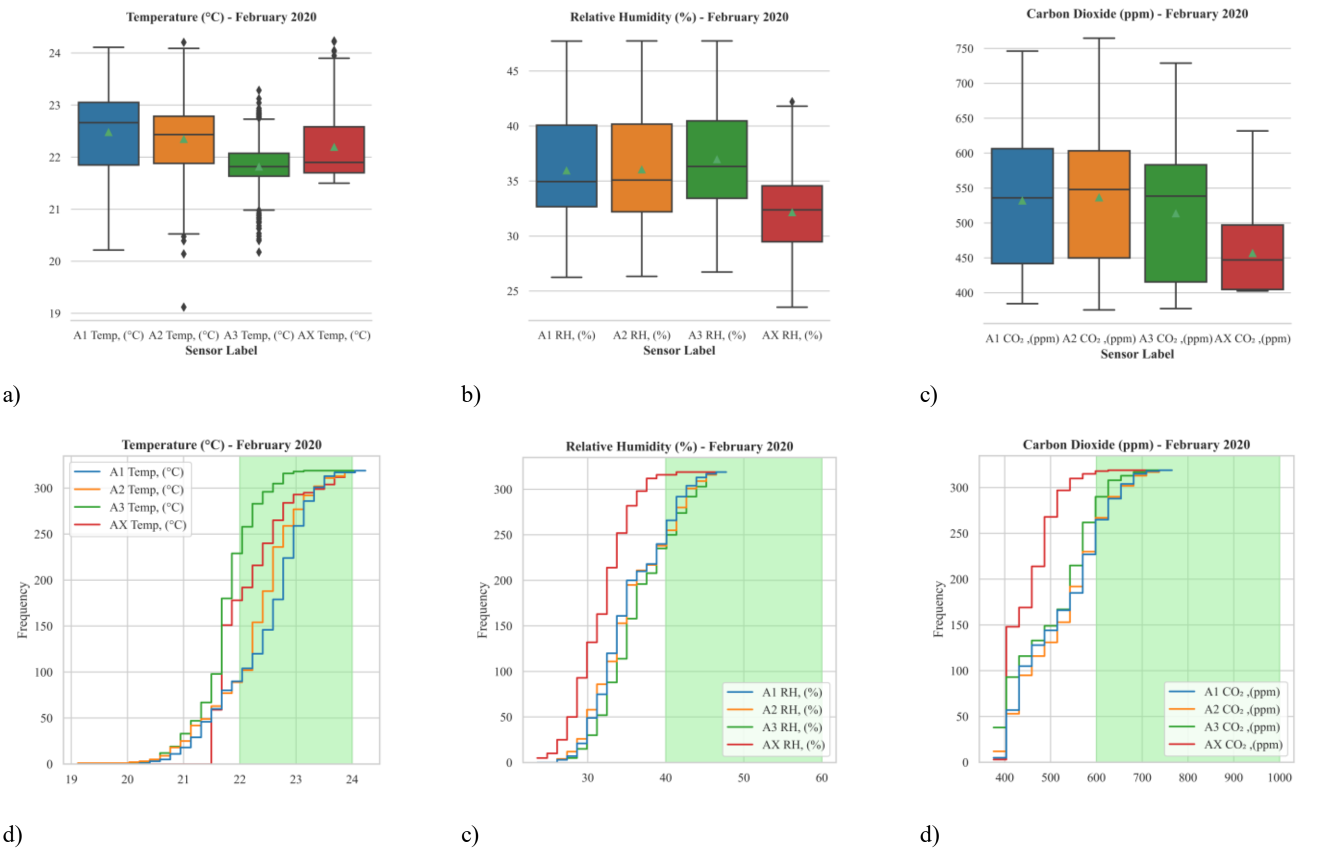



**Figure 2** (a) $t_a$ (°C) measurement distribution reported by each sensor (b) RH measurements distribution reported by each sensor (c) $CO_2$ (ppm) measurement distribution reported by each sensor (d) $t_a$ (°C) cumulative frequency distribution graph showing the distribution (smallest to largest) and frequency temperature range of each sensor, (e) RH (%) cumulative frequency distribution graph and (f) $CO_2$ (ppm) cumulative frequency distribution graph.

Monitor AX was the most consistent in monitoring data as the data varied much less compared to the HOBO MX1102 monitors A1, A2 and A3. However, the medians of the measured data for the AX monitor were different compared to the rest of the monitors and it had the maximum outlier observations for RH and $CO_2$. Monitor A3 had a closer median value compared to monitors A1 and A2 than AX monitor, and it was located closer to AX monitor by approximately 2.5-meters.

The differences in the medians for all sensors were relatively small and not practically significant. In addition, the collected data by the two types of monitors appeared to be highly correlated, with a value of 0.9 determined by 'Pearson product moment correlation'.

Same with the HOBO MX1102 A1, A2 and A3 monitors, the medians for RH and $CO_2$ levels were more similar to each other with a slight difference. However, the $CO_2$ levels appeared to be lower for the A3 sensor because the sensor was placed relatively distant from the occupant workplaces compared to A1 and A2 monitors. Based on these results, it is fair to assume that any of the A1, A2 and A3 sensor locations could provide representative data related to the $CO_2$ levels and RH for the examined open-plan office.

The difference in the temperature medians for all sensors was also relatively small but had a larger variation in the distribution in the open-plan office. The variation in the results exceeded 1°C. It is fair to assume that the differences in the temperature were mainly due to the heat sources from office equipment, occupants, and solar radiation through windows. Therefore, the distance between the sensor and the workplace(s) is important when it comes to the reliability of the measurements, especially if the sensor is a Building Management System sensor (BMS) controlling the ventilation system. Again, monitor A3 recorded lower temperature levels than A1, A2, and AX monitors because it was placed relatively distant from the workplaces. Also, it is worth mentioning that the placement of the A2 monitor was inappropriate as it was located near the window and a heat source (BSRIA AG, 2001). It was reported that the occupant seated near monitor A2 would move the monitor and place it on top of the windowsill, which may have influenced the reported results. As a consequence, monitor A2 has recorded a temperature difference of ±5 °C between the maximum and minimum temperatures during the month of February.

In regard to the influence of the monitors' locations on IAQ and the freshness of the air, the Ez was calculated and found to be 0.6, 0.6, 0.7 and 1.5 for $CO_2$ sensors A1, A2, A3 and AX, respectively. The average Ez from the four sensors reveals that the air distribution was well mixed in the open-plan office during the measuring period (CIBSE, 2015). Figure 3 displays the required ventilation rates for comfort and health for each of the $CO_2$ sensor locations using the calculated Ez.

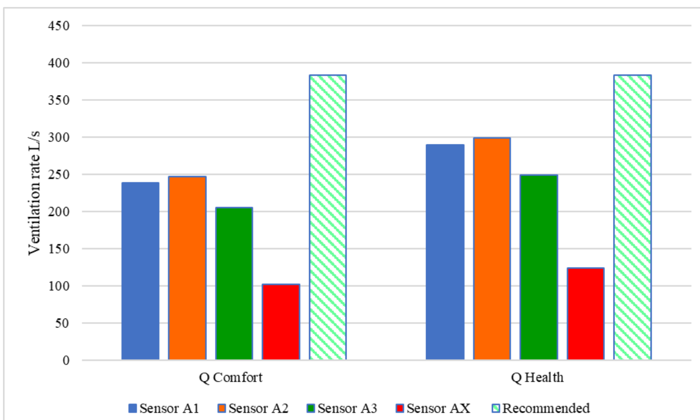


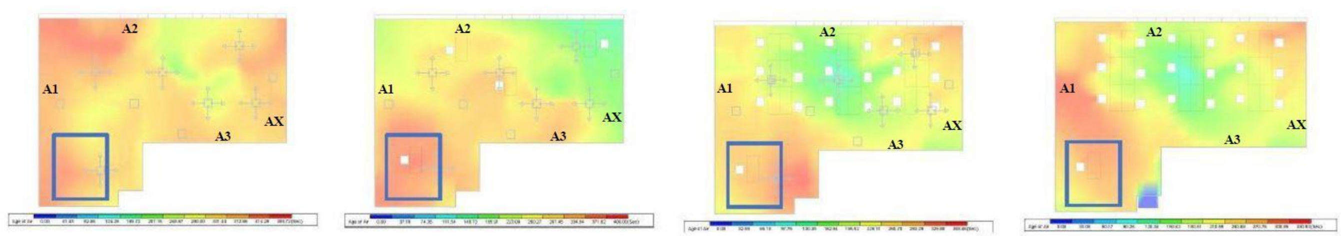

**Figure 3** (a) Calculated ventilation rates for comfort and health in the open-plan office using the calculated Ez at each sensor location.

The recommended supply rate for ventilation was significantly higher than the calculated ventilation rates for comfort and health in the open-plan office. The Ez value calculated from the $CO_2$ measured data of monitor AX was very high compared to the other monitors. An Ez value of 1.5 is usually achieved with displacement ventilation. Thus, the AX monitor resulted in a lower ventilation rate required for comfort and health. Note that monitors A1 and A2 were located closer to the workplaces and with less than 3-meters distance from the radiators. Both monitors had a larger distribution of temperature data recorded compared to the other monitors. The difference in temperature recorded by the sensor due to local heat sources may have led to a lower Ez value due to the difference between the supply air temperature and room air temperature recorded by the sensor.

The reported data by each sensor in this study confirms that the sensor's location could be critical in terms of effectively controlling the IAQ and thermal conditions of the space. The consequences of having a BMS sensor placed at not a representative location will falsely override the HVAC system for the rest of the areas in the space. This may cause thermal discomfort or potentially increase the energy demand.

### CFD Simulation Scenarios

The local mean age-of-air (LMA) was calculated for each scenario. All values were taken at the height of 1.5 meters. For the first CFD scenario simulated with no occupants, the maximum age of air was 455.72 seconds(sec), as the ventilation rate was set to 1.3 L/s/$m^2$. As for the second CFD scenario, including 4-occupants, the age of air improved by 10%, 12% in the third scenario with 19-occupants and 7% when the main office door was kept open. The freshness of the air increased due to the increase in the ventilation rate associated with each additional occupant. Figure 4 shows the area found in the open-plan office with the longest air for all scenarios marked with a navy-blue square. The occupant seated at that marked location would have the least fresh air compared to other locations in the open-plan office, especially the central locations. That is due to the number of supply diffusers in the central locations compared to the marked location and also due to the lack of openings. However, the temperature in that area was within the comfort range of the entire office. Assuming that the office was at full capacity and the ventilation rate was below the recommended value, the pollutants would accumulate at the marked location as the air remains for a more extended time, and the occupant seated at that location will be affected the most. It was observed from Figure 4 that the location of monitor A1 has the least air mixing compared to the rest of the monitors, followed by A2, A3 and AX, respectively. Thus, the calculated Ez agrees with the CFD results.




a) b) c) d)

**Figure 4** (a) CFD First scenario with no occupants (b) CFD second scenario with four occupants (c) CFD third scenario with 19 occupants (d) CFD fourth Scenario with 19 occupants and main office door open.

### CONCLUSION

This study provides results from field measurements and CFD simulations that can support decision making regarding the position of BMS and environmental sensors and the collection of indoor climate data in open-plan offices. In the specific open-plan example examined in this study, the measured data show little differences in RH and $CO_2$ levels between the monitors. A larger difference was found for temperature distribution. It is fair to conclude that local heat sources contributed to this change since the measured period was during the cooling season (winter) when the heating plant was in operation. The calculated Ez from the $CO_2$ measurements indicated that air distribution was well mixed (where the sensors were located) in the open-plan office during the measuring period. However, the Ez varied significantly across the office. The CFD simulation results identified the regions in the office with the least air freshness and the location of the occupant who would most be affected when certain pollutants reach the TLV. The region found was with the least air supply and had no openings except for the open-plan office main door.

Finding the optimal location to monitor and control the space's IAQ and thermal conditions achieves health well-being objectives and may positively influence energy consumption. As the results of this study are based on just one open-plan office with an induction system under specific weather conditions, it is recommended to further develop the application of the method in more varied office settings, occupant demographics, and outdoor weather conditions for further conclusions and recommendations to be formulated. Also, a better understanding of the collection and analysis of monitored data, extending over a long-time period, is required.

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