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Placement and utilization of CO_2 measurements in the ventilation and occupancy assessments

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Abstract. Continuous carbon dioxide measurements have typically been used to adjust the demand-based ventilation. With the global COVID-19 pandemic, the use of measurements to ensure the functionality of ventilation and to assess the utilization rate of the space has increased in importance due to the significant impact of air exchange on the spread of the disease via aerosols. The work aimed to examine the spread of carbon dioxide in the room and how the location of the sensors and space users affects the measurement result. In our study, six carbon dioxide sensors were placed in the room that serves as a teaching restaurant. Five sensors were placed in the space itself and one sensor in the exhaust valve. Two meals were arranged, each attended by 10 people. The location of the persons in the space was also monitored. Based on the measurements, it was assessed how the air distribution of the space and the location of the users affected the measurement result of carbon dioxide. It was found that the carbon dioxide content measured close to diners differed from the result measured in the exhaust duct. Because the air in the exhaust duct is mixed with more fresh supply air than in the vicinity of the dining table, it can be thought that the concentration measured in the exhaust duct can indicate better the air variability of the whole space. On the other hand, sensors located closer to the seating area are potentially better positioned from the demand-based ventilation point of view. In the future, it will be necessary to study the issue in more detail for different types of premises and to examine the application of ventilation and space utilization assessment to real-time monitoring of the risk of airborne infectious diseases, for example.

Keywords. Ventilation, Carbon Dioxide, COVID-19, Occupancy
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1. Introduction

Over the recent years, measuring room carbon dioxide levels in buildings and using this information to either control ventilation or collect data on the conditions has increased. A question that arises, however, is how well the installed measurement corresponds to the actual levels of CO_2 in a room and which are the factors that may cause discrepancies between the two.

Since the beginning of 2020 SARS-CoV-2 virus and its different variations have spread throughout the world and there have been numerous research papers attempting to describe the transmission of the virus in different kinds of settings. Some papers, for example, emphasize the role of airborne transmission and consequently, the role of ensuring sufficient indoor ventilation becomes one of importance. [5] Mathematical models have been formulated to estimate the probability of transmission of respiratory pathogens in indoor settings. One of these models is the Wells–Riley infection model which among other factors takes into account the room ventilation rate. [2]

CO_2 can be used as a control parameter for demand-based room ventilation control. Additionally, it can also be used in the evaluation of the sufficient room ventilation rate. Thus, indirectly a connection between CO_2 levels and virus transmission probability may be formulated further underlining the need for reliable CO_2 measurements.

In this paper, we present a pre-study test and demonstration methodology for examining the effect of placement of the CO_2 measuring devices on the measured results. The placement is examined in relation to supply and extract terminals of ventilation but also in relation to occupant placement and distribution. Additionally, we demonstrate a concept of data collection on CO_2 levels and occupancy rates that may be used to further examine sufficient ventilation rates and airborne infection risk probabilities.

1.1 The effect of carbon dioxide on human health and cognitive abilities

As humans spend time indoors exhaling produces carbon dioxide and this will elevate the concentration of CO_2 in the room. The effects of elevated CO_2 levels on human health and decision-making have been widely discussed. For example, Satish et.al. have found that some moderate decrements in decision making may occur already on CO_2 levels between 600…1000 ppm [7]. On the other hand, some studies critique that some of the research on the issue may be inconclusive. Du et.al. argue that some cases may have failed to achieve uniform distribution of CO_2 inside the room where experiments on cognitive performance have been made and thus the inhaled amount of CO_2 is not accurately known [3]. This begs the question: If the CO_2 concentration is non-uniformly distributed, could this happen in any significant amount, and if so, in what kind of settings could this occur?

1.2 CO_2 measurements and mechanical ventilation control

CO_2 concentration can be used to control mechanical ventilation inside a room via a variable air volume ventilation system. This can be achieved for example by setting a corresponding air exchange volume to the CO_2 concentration value. The air exchange rate will in this case increase linearly as the CO_2 concentration rises. This kind of control is typically used to restrict ventilation to a minimum level needed to maintain indoor conditions thus saving the fan power and energy needed to heat or cool the air.

Additionally, if it's assumed that air is fully mixed inside the room, dependence between the room ventilation rate, the number of occupants, and the CO_2 concentration can be derived using a fully mixed mass balance model. If two of these are known, the third one can be calculated. For example, Franco et.al. [4] have used that model in their article as follows:

$$V\frac{dC_{CO2}(t)}{dt} = \dot{r}\, n_{occ} - \dot{m}\,(C_{CO2}(t) - C_{ext})$$

where C_{CO2} is the concentration of CO_2 inside the room, V the total volume of the room, n_{occ} the number of occupants, $\dot{r}$ the CO_2 generation rate per person, $\dot{m}$ the airflow rate due to ventilation, and C_{ext} is the CO_2 concentration in the supply air. [4] Thus, if the number of occupants is known the CO_2 concentration can be used to determine the ventilation rate. Conversely, if the ventilation rate is known CO_2 concentration can be used to determine occupancy.

1.3 SARS-CoV-2 transmission mitigation

Ventilation has been found to play a major role in mitigating the transmission risk of the SARS-CoV-2 virus.
Many respiratory pathogens may spread through small respiratory aerosols that can stay airborne for extended periods of time [8].

One of the key factors in the probability of transmission of a virus pathogen via indoor air is the airborne concentration of infectious quanta (quanta/m^3). The larger the quanta the higher the probability of the infection is. Naturally, the amount of ventilation in the room will influence the quanta and studies have found that increased ventilation will reduce the risk of infection as it will lead to diluted quanta concentrations. For example, Miller et.al. show the modelling of the Skagit Valley Chorale super spreader event using the Wells–Riley formulation and what role the ventilation rate would play in such an event [6]. Burridge et.al. studied the applicability of CO_2 measurements in airborne infection risk modelling and concluded that there is a clear need for better mitigation of the airborne spread of the SARS-CoV-2 virus. Building on this notion they also recommend more widespread use of CO_2 monitoring in occupied spaces to ensure sufficient ventilation. [1]

2. Research Methods

2.1 Test room and participants

Catering Studio, a learning environment for Hospitality Management students was the test room in this study. It is composed of two different kitchens, a bar, and a restaurant area. All the measurements were done in the restaurant area, and it worked as a living lab situation to study customers' behaviour while having a buffet lunch. Two one-hour settings were served with ten customers in each. All the diners were taking part in the study voluntarily. Participants got information about the study, hand hygiene, and safe distances.

During the experiments, the room was mechanically ventilated. The air distribution system is mixing ventilation with supply air terminals located in the ceiling in the middle of the room and extract air terminals in the ceiling at the end of the room. The placement of the terminals is presented in Fig. 1. The ventilated airflow was 400 L/s supply and 400 l/s extract air. This air exchange rate corresponds to 5,3 L/s, m^2 and 40 L/s per person (10 persons in the room during the study). The ventilation airflows were observed via the building automation system.

2.2 CO_2 measurements

The CO_2 measurement system consisted of 6 sensors that measured temperature and CO_2 value. The sensors were placed in the locations shown in the floor plan (Fig. 1). The sensors 1, 3 and 5 were on the floor about 1.6 meters high, which is close to the typical installation height of a room sensor and also close to the average height of breathing of a standing person. The table-level sensors (2 and 4) were about 0.5 meters above the table surface. In addition, one sensor was placed in the exhaust air duct (sensor 6). In addition to the CO_2 sensors, the data for the building automation measurement of the space were stored. The sensors used were Miran DLS-system sensors for CO_2 and relative pressure (Fig. 2). As the purpose of this experiment was to test and demonstrate the method it was not seen necessary to further calibrate the sensors at this point and thus, they were in factory calibration. This can be seen as a possible source of some inaccuracies in the results.

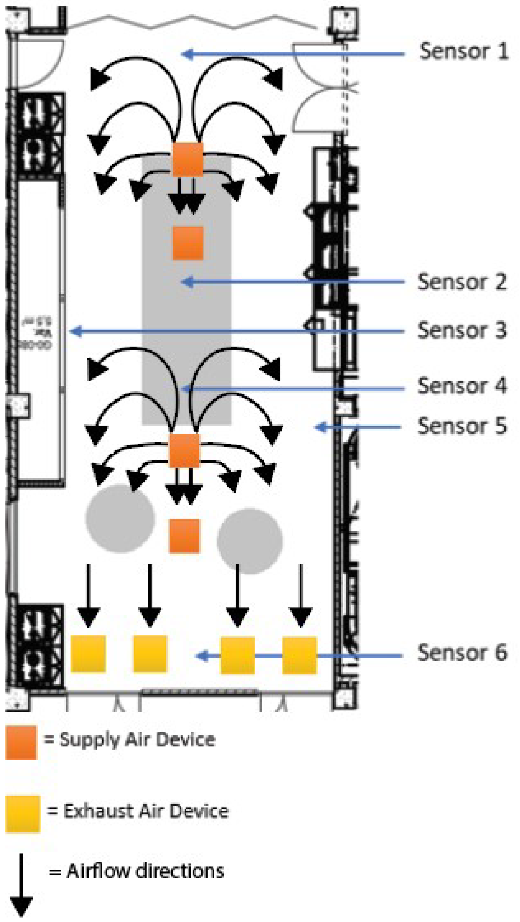

Fig 1: Positioning of the CO_2 sensors, air devices and estimated airflow directions in the room.

Fig 2: Miran DLS IAQ.THB+CO2+DP sensor used in CO_2 measuring

2.3 Personal position tracking

Noccela ID Badge is a UWB based proximity detection device for social distancing and contact tracing, and it sends the contact data to the server via a UWB beacon for Contact Tracing (noccela.com). In this study, it was used to get the position data of the persons in the test room. When the customers entered the restaurant area, they were given these personal badges and they carried them during the lunch.

3. Results

Temporal variations of CO_2 concentrations in the room measured by the sensors are shown in Fig. 3. All the sensors showed a CO_2 level increase when the persons entered the room, but there were some differences between the sensors based on their location in the room. Also, the tracked position of the persons affected the results. Position data of the persons in the room is shown in Fig. 4.

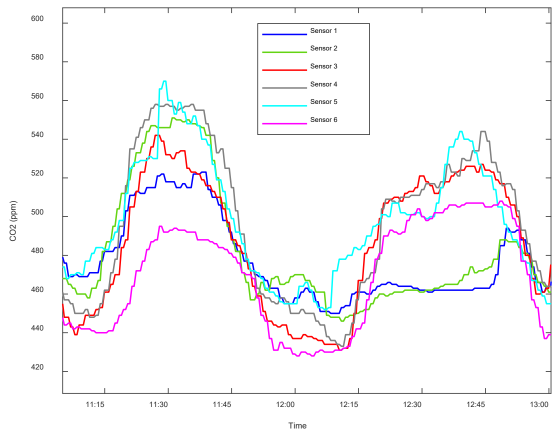

Fig 3: CO_2 concentrations in the room measured by the sensors 1-6.

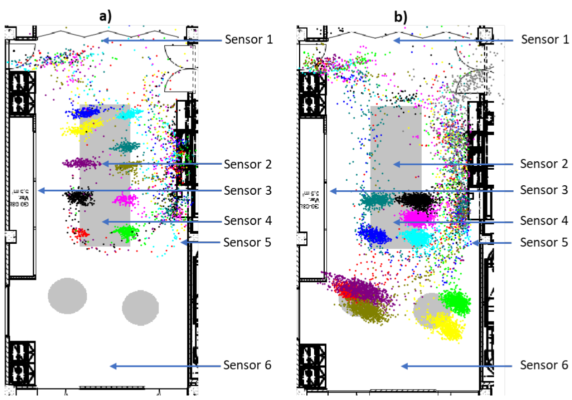

Fig. 4: Positional data of persons in the room **a)** during the first setting (11:00–12:00) and **b)** during the second setting (12:00–13:00). The colours indicate different persons.

During the first setting (11:00-12:00) all the persons had their position mostly at one table far away from the exhaust duct. CO_2 levels of the sensors 2, 4, and 5 showed the highest concentrations as they were located close to the breathing zone of the persons. The sensors 3 and 1 showed a bit lower levels as they were not located so close. The sensor 6 in the exhaust duct showed the lowest CO_2 level. The difference in the breathing zone sensors 2 and 4 was about 70 ppm due to CO_2 dilution before the exhaust duct. The difference in the time of the rising CO_2 between the exhaust duct sensor 6 and the other sensors is about 5 min.

During the second setting (12:00–13:00) the persons chose their seats at three different tables. Now, the sensors 2, 3, and 5 showed the highest values and similar trends as they were located close to the breathing zone. The sensors 1 and 2 showed the lowest CO_2 levels as they were located not so close to the persons and upstream of the airflow in the room. Interestingly, the sensor 6 in the exhaust duct showed higher values compared to the sensors 1 and 2 and similar values compared to the sensors 2, 3, and 5.

4. Discussion and recommendations

Measuring indoor carbon dioxide concentration can have many purposes. On the other hand, it can be used to control mechanical ventilation but also it is usable for monitoring the indoor air quality to ensure healthy indoor conditions. Both aforementioned uses of CO_2 measurements are can already be found in mechanically ventilated spaces. We propose another use for the measurement in the mitigation of transmissible respiratory pathogens. As CO_2 concentration inside a room can be used to derive the ventilation rate in the room it can also be used to derive the approximate probability of the infection. CO_2 measurements provide real-time data, and the infection probability can also be modelled in real-time. Zivelonghi et.al. also discuss this possibility in their research. [9]

Based on the presented results, it can be said that positioning of the sensors in relation to the air stream and persons in the room is important. The CO_2 sensor in the exhaust duct gives an average status and variations of CO_2 levels in the room, but using more sensors, especially close to the breathing zone, provides more accurate information about the exposure to CO_2 and other compounds in exhaled air including also potential pathogens.

While the modelling and calculation of infection probability with different models cannot be considered to provide absolute probabilities but only approximations, the connections between CO_2 concentration, ventilation rates and infection probability in occupied spaces are clearly shown. This lays an interesting foundation for future studies where infection probability could be calculated in dynamically altering situations based on real-time data collection. This could, in effect, lead to the real-time presentation of the infection risk. It's important to note, however, that it should also be studied further how this information on infection probability could or should be effectively used in mitigation.

5. Conclusions

The concept of several CO_2 sensors and personal position tracking data were tested in the restaurant setting to study CO_2 levels in different locations in the room in relation to persons and ventilation. The location of CO_2 sensors is important: human exposure to CO_2 and other respiratory compounds and potential pathogens is best obtained when the sensors are close to the breathing zone.

The CO_2 measurements can traditionally be used for different functions involving the control of ventilation and indoor air quality. Additionally, in this paper, we support another proposal for the mitigation of transmission of respiratory pathogens. Furthermore, as the CO_2 concentration is unlikely to be uniformly distributed inside a room the placement of the sensor will have importance on the reliability and accuracy of the measured data.

In this paper, we demonstrated a data collection method that can be used to evaluate the effect the placement of a CO2 sensor has on the results and also how occupant placement and distribution can simultaneously be monitored. Further research is needed in different kinds of settings to weigh how each factor may affect the measured results and what practical importance it may have. For example, different purposes i.e., ventilation control, pathogen mitigation and occupancy estimation may demand different kinds of considerations for CO2 sensor placement. The method demonstrated in this paper can be used to take these different factors into consideration i.e., placement and height of the sensor, the amount of ventilation and the number and location of occupants.

6. Acknowledgement

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Data access statement

The datasets generated and analysed during the current study are not available because unfinished studies and agreements between cooperating projects, but the authors will make every reasonable effort to publish them in near future.