CO_2 levels as an indicator of ventilation performance in mechanical ventilated buildings

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Abstract. The current COVID-19 pandemic has attracted considerable attention from the general public and researchers. To increase this resilience toward global pandemics, we urgently need a deeper understanding of effective protection strategies. During the COVID-19 pandemic, more evidence confirms that airborne transmission plays an essential role in spreading pathogens. The ventilation systems play an important role in removing pathogens from indoor air. The current paper focuses on examining the air ventilation performance of the existing building stock before Covid 19 pandemic. The study was carried out in mechanical ventilated 440 spaces in four different building types by comparing the obtained individual CO_2 concentration data with the maximum concentration values given by official regulations, recommendations and guides. The data was obtained from the property maintenance program for one month at 5-15 minutes intervals. The risk spaces were studied in detail, and the risk analysis was conducted by applying the Wells-Riley approach. The research proposes recommendations for utilising air ventilation systems in different applied cases.

Keywords. Indoor air quality, Carbon dioxide, COVID-19, Ventilation system
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1. Introduction

The COVID-19 disease caused by the pathogen identified as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread worldwide, resulting in a global pandemic. Studies have revealed that SARS-CoV-2 is spread human-to-human through close contact, respiratory droplets, fomites, and contaminated surfaces predominately in indoor environments [1]. Therefore, ventilation of the premises is of great importance in controlling Covid-19 infection. Poorly ventilated places are considered a high risk of infection and occupants' exposure [2].

Carbon dioxide can be considered an indirect but very objective indicator of indoor air pollution [3]. Concentrations of carbon dioxide in indoor air are mainly due to two factors such as carbon dioxide concentrations in outdoor air (about 400 ppm) and the metabolism of people in the premises (exhaled air about 50,000 ppm). Without proper ventilation, CO_2 concentrations in premises will rise rapidly to high levels. In previous studies, carbon dioxide monitoring has been used to identify measures to improve ventilation in settings such as schools and offices [4]. However, excessive carbon dioxide levels have also been connected to headaches, fatigue and reduced work capacity [5]. In addition to that, the risk of indoor airborne infection transmission could be directly estimated via measurements of CO_2 in well-mixed conditions [6].

The Wells–Riley model has been widely used for quantitative infection risk assessment of respiratory infectious diseases in indoor premises [6]. The method has been already adopted to calculate the infection risk for different activities and rooms using a standard airborne disease transmission Wells-Riley model calibrated to COVID-19 with the correct source strength (quanta emission rates) [7]. In this study, the Wells–Riley model is applied to predict the risk to get infected by coronavirus calculated with quanta values for the Delta variant of the virus.

This study aims to show the preliminary approximate results on the effect of ventilation on the spread of coronavirus by air. In addition, the carbon dioxide concentrations in the indoor air are under consideration. Finally, the study provides a general overview of the predicted risk of coronavirus in different building types.

2. Methods

This study aims to review current regulations, guidelines, and recommendations regarding the CO_2 concentrations in premises and design airflow rates. The research also focuses on how the CO_2 concentrations measured before the corona pandemic in the different building types relate to the recommendations for maximum CO_2 concentrations. The study compared measured individual CO_2 concentration data with the maximum CO_2 concentrations given by official regulations, recommendations and guides. The recommended limit of 800 ppm issued by REHVA guidelines [7] and Decree 1009/2017 [8] was used as a starting point for evaluating the carbon dioxide concentration data.

2.1 guidelines related to CO$_2$ levels

As part of the study, current government regulations, guidelines, guides and studies were reviewed. Table 1 summarises the maximum concentrations of CO$_2$ following regulations, standards, guides and recommendations.

Table 1 summarises the most relevant regulations, guidelines, and recommendations that affect ventilation design and carbon dioxide levels in buildings. [7-11]. The carbon dioxide concentrations recommended by REHVA in the Covid-19 pandemic [7] are in line with the maximum concentrations of the current regulation 1009/2017 [8], 545/2015 [9] and the indoor air classification S1 and S2 indoor climate categories [10] and building code [11].

Tab. 1 - Maximum levels for carbon dioxide.

	Guidelines, regulation	CO$_2$ level (maximum)
Regulation	1009/2017; 5 §	800 ppm (1 450 mg/m^3)
	545/2015; 8 §	1 150 ppm (2 100 mg/m^3)
Building code	D2 National Building Code of Finland	1 200 ppm (2160 mg/m^3)
Guidelines	Valvira's Environmental Health	1 150 ppm (2 100 mg/m^3)
	Healthy facilities (Terveelliset tilat)	1500 ppm (tyydyttävä taso)
Recommendations	Finnish classification of Indoor climate	
	indoor climate category S1	350 ppm + outdoor concentration
	indoor climate category S2	550 ppm + outdoor concentration
	indoor climate category S3	800 ppm + outdoor concentration
	REHVA COVID-19 Guidance	
	- minimum area/person 7 m^2	800 ppm
	- minimum area/person 10 m^2	1 000 ppm

Exposure to indoor air via Covid-19 aerosols is very high in poorly ventilated rooms. Therefore, REHVA recommends maximum concentration limits of 800 ppm and 1000 ppm during a Covid-19 pandemic, depending on other factors in the space. Table 2 summarises the design air volumes for the room types covering the measurement data. At the air volumes in the table, the CO$_2$ concentrations should not exceed the CO$_2$ concentrations in the regulations.

Tab. 2 – Design airflow rates.

Room type	**Design airflow rate dm^3 / s / m^2**
Office / Open Office	1 / 2
Restaurant	10
Class 1 / Class 2	3 / 4
Library	2
Patient Room 1 / Patient Room 2 / Operating Room	2,5 / 1,5 / 30
Retail space 1 / Retail space 2	2 / 4
Meeting room 1/Meeting room 2	3 / 4
Educational building	
minimum area/person 7 m^2	2
minimum area/person 10 m^2	1

Carbon dioxide data for February 2019 were available for the research project. The measurement data is obtained from Granlund Manager software, cloud-based property management and energy management software. Due to the anonymous processing, no precise building data are known for the CO$_2$ concentrations of the obtained premises. Therefore, the following information has been used for the measurement data: date and time, room type, sensor name, and CO$_2$ concentration. The interval of the measurement data is from 5 minutes to 15 minutes, depending on the status. The measurement time is 01.02.2019 - 28.02.2019. The time before the corona pandemic with ordinary usage of indoor premises was chosen as the time of measurement. Table 3 shows the number of spaces and measuring points by building type.

Tab. 3 - Number of spaces and measuring points by type of building.

Building type	Series	Spaces	Measurement points
Office	A	67	193 114
Office	D	88	722 112
Shopping centre	B	44	157 199
Shopping centre	C	7	88 704

Hospital	E	3	14 415
Educational building	F	231	661 174

2.2 *Wells–Riley approach for infection risk assessment*

The Wells–Riley equation [6] is based on the concept of a hypothetical infectious dose unit: 'the quantum of infection'. A 'quantum' is a core value and a specific term for this method. Wells defines it as the representation of infectious dose, where inhalation of one quanta leads to a probability of infection of 63%. The current study applied the quanta emission rates (66th percentile) for the Delta variant of SARS-CoV-2 and breathing rate values depending on time-weighted averages of occupant's activities [7]. The model calculates the individual probability of infection of susceptible persons for which acceptable values can be calculated from the event reproduction number (R).

3. Results

The facilities and their measurement data were examined by choosing a carbon dioxide concentration limit of 800 ppm. Table 4 summarises the number of premises by building type with carbon dioxide concentrations <800 ppm and ≥800 ppm. Measurement data were observed for the entire measurement period. If the concentration limit of 800 ppm was reached momentarily in the premises, it was considered to be above the concentration limit of 800 ppm (≥ 800 ppm).

Tab. 4 - Number and share (%) of premises by the building type with a CO_2 emission limit of 800 ppm

Building type	Carbon dioxide concentration	
	≥ 800 ppm	< 800 ppm
Office, Series A	41 (62 %)	26 (39 %)
Office, Series D	33 (38 %)	55 (63 %)
Shopping centre, Series B	9 (21 %)	35 (80 %)
Shopping centre, Series C	0 (0%)	7 (100 %)
Hospital, Series E	1 (33 %)	2 (67 %)
Educational building, Series F	164 (71 %)	68 (29 %)

The CO_2 concentrations above 800 ppm were temporarily reached in all room types. In the shopping centre premises, the average level of the concentrations was the lowest. In 80% of the shopping centre premises, the concentration limit of 800 ppm was never reached during the measurement period. The worst situation was in the teaching facilities, where only nearly 30% had carbon dioxide concentrations below 800 ppm. For hospital facilities, measurement data were available for only three facilities. Therefore, the results are too limited to make some valuable conclusions. However, it should be noted that the time taken to exceed the concentration of 800 ppm is not taken into account.

3.1 *CO_2 concentration profiles*

The next step in processing the measurement data is to focus on periods when the steady-state concentration exceeds 800 ppm in the office (series A), shopping centre (series B) and educational building (series F). Figures 1-3 depict the concentration profiles measured at the same day measured in different premises. The premises are marked with the measurement series letter (A, B or F) and the sensor number. Every space is presented by one CO_2 sensor. The general occupancy period is marked with dash lines to differentiate the occupied and unoccupied periods.

The carbon dioxide concentration measurements in the office premises (Fig.1) show typical occupation profiles with two main working periods (3-4 hours) and a lunch break (about an hour). Apparently, the occupancy schedule depends on the use of the office premises and working regime. In most cases, after the occupancy period, the CO_2 concentration returns to the lever before the occupancy.

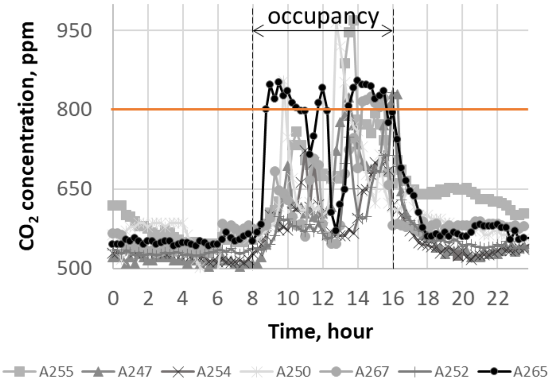


Fig. 1 - CO_2 concentration profiles in the office building

The occupancy varies during the working day in the educational building (Fig. 2a, b). The active period lasts about 4 hours in general. The results revealed the premises with different ventilation schedules. In some cases (Fig. 2a), the CO_2 concentration returns to the initial values after the occupancy period. In the other cases (Fig. 2b), the concentrations grow a certain time after the occupancy period. Different ventilation schedules could influence ventilation schedules when in the other cases (Fig. 2b), the ventilation airflow rate is significantly reduced or turned off during the unoccupied time.

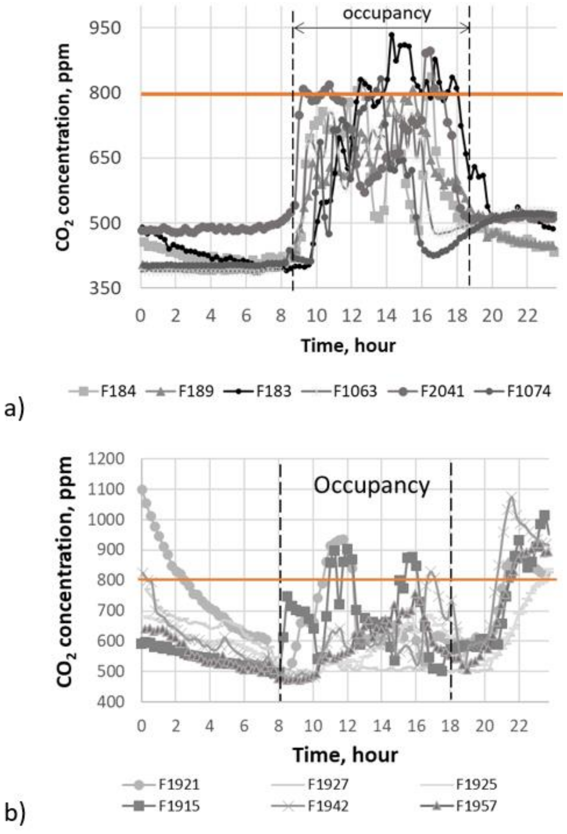


Fig. 2 - CO$_2$ concentration profiles in the educational building

The CO$_2$ concentrations in the shopping centre rise steadily, depicting the gradual growth of the occupancy with the typical maximum values between 4-6 pm. After the occupancy time, the concentration steadily returns to the unoccupied period values.

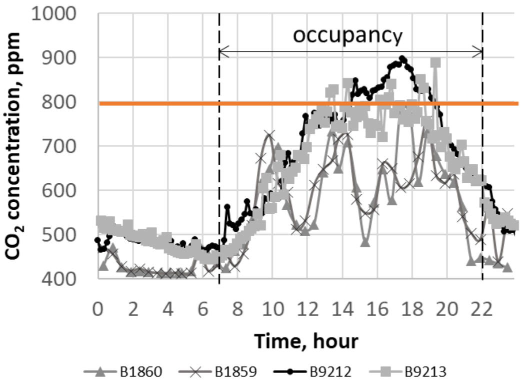


Fig. 3- CO$_2$ concentration profiles in the shopping centre

The growth of CO$_2$ concentration indicates the population density in all the studied cases, which enables the estimation of occupancy. In contrast, the exceeded CO$_2$ levels during the unoccupied time could result from insufficient ventilation schedules.

3.2 Infection risk assessment with the Wells–Riley approach

Since the measurement data are not enough to directly apply the Wells–Riley risk assessment method, there is a need to assume the initial data for the Wells–Riley approach to risk assessment (Table 5). The room size in all the cases is the same, the room area is 80m^2, and the room height is 3 m. The specific airflow rates are selected from the current building codes based on the assumption that the ventilation systems have been designed according to them. Finally, the measurements of carbon dioxide concentration gave information about the average occupancy time and the number of occupancies.

The measurement results marked with black are used later for the occupancy assessment from carbon dioxide measurements. The occupancy assessment is based on a fully-mixed dynamic mass balance model simplified by the steady-state assumption [12]. The final number of occupants should give the closest fit to the measurement data. The study applies the generally accepted assumption for ventilation sizing purposes that one infectious person stays in the room throughout the event. The occupancy time in offices and educational buildings is estimated based on the analysis of CO$_2$ concentration profiles. The average occupancy time in the shopping centre is assumed based on the research data [13].

Tab. 5 – Estimated parameters of the rooms

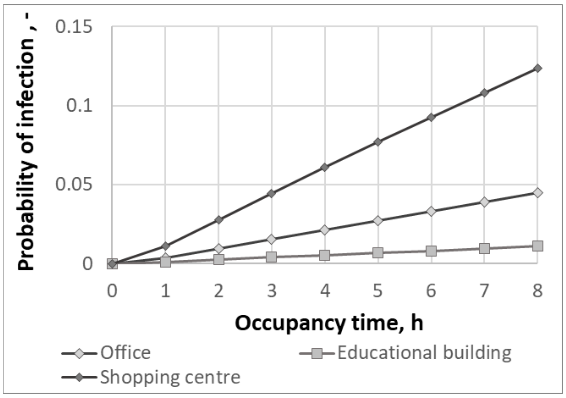
Room	Ventilation rate, L/(s m^2)	No of susceptible persons	Occupancy time, hour
Office	1.125	8	3
Educational building	4	28	4
Shopping centre	1.5	7	0.5

The results (Table 6) show the significant effect of the quanta value and averaged breathing rate on the probability of infection. The higher quanta and breathing rate values in educational buildings than in offices result in a higher probability of infection. At the same time, the event reproduction number highly depends on the calculated occupancy time.

Tab. 6 – Probability of the infection

Room	Quanta emission rate, quanta/h	Breathing rate, m^3/h	Probability	R event
Office	5	0.65	0.015	0.12
Educational building	3.2	0.6	0.004	0.15
Shopping centre	8.4	1.32	0.004	0.03

Figure 5 shows the calculated rise of the probability of infection and event reproduction number during 8 hours. However, the probability of infection in the education building remains the lowest compared to the office building and shopping centre results. At the same time, the event reproduction number in the office and education building showed comparable values during the chosen period.



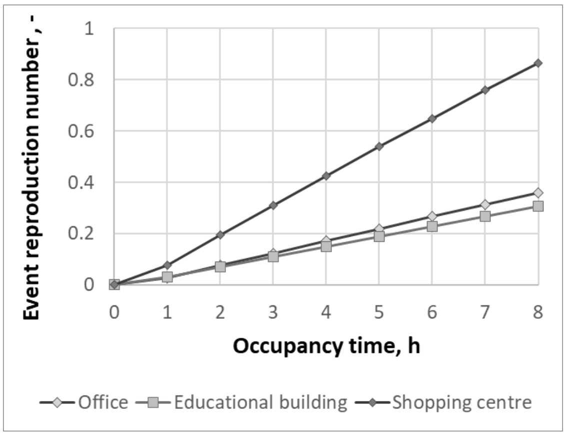


Fig. 4- Probability of the infection and the even reproduction number for the studied cases

4. Discussion

The measurements of CO_2 concentration give general information about ventilation efficiency and approximate occupancy. However, risk assessment of coronavirus infection needs to consider other essential parameters [14]. For example, crowded indoor environments and air exchange rates could also lead to the reproduction number R0 > 1 with reduced exposure times. In addition, occupants' expiratory and physical activities could lead to high quanta concentrations and breathing rates, resulting in increased infection risk. Thus, the comparatively highest carbon dioxide levels during the measured period in the educational building did not lead to the highest risk of infection because the quanta concentrations and breathing rates were the lowest in this case. Nevertheless, in general cases, the real-time monitoring of carbon dioxide concentrations can be applied to ensure adequate air ventilation, which prevents SARS-CoV-2 transmission [15].

The methods presented in the study include some limitations and uncertainties related to the lack of measurement data and the Wells–Riley method. The Wells–Riley equation assumes steady-state conditions. It requires measurement of ventilation airflow rates and occupancy, which are frequently difficult to measure, often vary with time, and in many cases are inaccessible because of security reasons.

Carbon dioxide monitoring could be not fully efficient in situations where exhalation is not the only CO_2 source [16]. Furthermore, CO_2 monitoring is not able to consider the mechanisms for the removal of infectious aerosols, such as virus deactivation, deposition, and filtration. In addition, the virus generation mechanisms through coughing, loud talking and singing might not correlate with corresponding CO_2 generation [17]. Thus, further studies are needed for monitoring carbon dioxide to quantify the risk of indoor airborne transmission of coronavirus infection. Nevertheless, the results give a general overview of the probability of infection considering the limitations mentioned above.

5. Conclusions

Even though the measures to prevent SARS-CoV-2 transmission were recommended in all European countries following the WHO, the exceeded contaminant levels are observed in many buildings due to high occupancy density inside enclosed environments for several hours a day. It could result in relatively high SARS-CoV-2 transmission probability. Therefore, ventilation systems should be adopted to guarantee more effective fresh air exchanges. The measurement data considered in this study were anonymous, and only the state type, sensor, time, and measured CO_2 concentration were known. It was not known, for example, the year of construction, address or opening hours of the holding. There are significant differences between the different room types based on the measurement data. In the case of shopping centre premises, about 80 per cent of the premises remain below the concentration limit of 800 ppm throughout the measurement period. However, in teaching premises, the same situation is present in less than 30%. Based on the CO_2 concentration results, conclusions can be made related to the ventilation efficiency concerning the use of the premises.

The results show the significant effect of the quanta value and averaged breathing rate on the probability of infection. The higher quanta and breathing rate values in educational buildings than in offices result in a higher probability of infection. As the study progresses, the situations where specific expiratory and physical activities should be considered can lead to high quanta concentrations and risk in large and closed environments.

6. Acknowledgement

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