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Occupancy Impact on Air Quality in Repurposed Museum Space

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ABSTRACT

This study investigates the air quality and ventilation effectiveness in a repurposed museum space with a hybrid ventilation system in Ljubljana, Slovenia. Focusing on CO_2 and particulate matter concentrations, the aim is to determine the correlation between these parameters and the suitability of the ventilation system following a change in space use. Measurements were conducted over a four-month period, analyzing data during different occupancy and ventilation scenarios. The study compares observed values with World Health Organization (WHO) guidelines, specifically targeting $PM_{2.5}$, PM_{10}, and CO_2 concentrations. Findings reveal inadequate ventilation in the repurposed museum space, even with hybrid ventilation. CO_2 concentrations correlated with $PM_{2.5}$ and PM_{10} levels, suggesting CO_2 monitoring as an indirect indicator of overall air quality. Recommendations include improving ventilation efficiency and limiting occupancy to ensure adherence to air quality standards.

Keywords: air quality, ventilation, CO_2, aerosols, indoor environment

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INTRODUCTION

Indoor air quality (IAQ) is becoming an increasingly visible parameter of the internal environment. In addition to indoor temperature and relative humidity, there has been a lot of research in recent years on adequate indoor and outdoor air quality. During the SARS-CoV-2 pandemic, adequate and sufficient ventilation proved to be a key measure in preventing the spread of the disease [1, 2]. The same is true for other pathogenic particles [3]. Air quality also depends on other pollutants such as particulate matter and CO_2 concentration [4]. Some pollutants are not well perceived by humans, even though they have an impact on health [5]. It is therefore important to control the levels of pollutants that have a negative impact on humans in space. Standards are ensured by properly designed HVAC systems. Purpose-built buildings must have adequate ventilation designed in by design, based on occupancy and use, to ensure minimum standards. In high occupancy areas, more attention needs to be paid to maintenance and to assuring the adequacy of the installed systems. There are several studies carried out in teaching spaces in older buildings where the ventilation is only natural and is not sufficient to meet the minimum requirements [6, 7, 8]. Sometimes, years after construction, some buildings change use and the conditions for a suitable indoor environment change. When more people are indoors, more pollutants emitted by general human activity are trapped in the indoor environment. The amount of CO_2 emitted by an individual depends on the time spent indoors and the level of activity. CO_2 is a known indicator of the general condition of the indoor air and is an indicator of other indoor pollutants and thus of the adequacy of ventilation [9, 10]. The amount of particulate matter or PM in the air depends on the ambient air and the activity in the room. High levels of PM in the air have a negative effect on the respiratory system. Research has linked high levels of PM in the air to the development of respiratory diseases as well as cardiovascular diseases [11-14].

The amount of particulate matter or PM in the air depends on the ambient air and the activity in the room. High levels of PM in the air have a negative effect on the respiratory system.

The purpose of the study was to analyse the existing air quality in a showroom with a hybrid ventilation system. The building has been repurposed for the current use. The measurements were carried out in a museum space in Ljubljana. We were interested in the correlation between CO_2 and particulate matter concentrations and the suitability of the new ventilation with the change of use. We want to find out if it is possible to assess the air quality of the room and the adequacy of the ventilation with a known CO_2 value alone. WHO guidelines dictate particulate matter values for an 8-hour average of 15 μg/m³ for $PM_{2.5}$ and 45 μg/m³ for PM_{10} [15]. The maximum recommended indoor CO_2 concentration is 1000 ppm. The goal of this study is to assess the effectiveness of air quality and ventilation in a repurposed museum space with a hybrid ventilation system and based on the findings, recommendations for improvement will be given to the museum.

The maximum recommended indoor CO_2 concentration is 1000 ppm.

This paper consists of three more sections. The remainder of this paper is organised as follows. The location and the measurement procedure are presented in the methods section, where we also present the experimental part. In the Results and Discussion section we comment on the results of the measurement. The conclusions are drawn in the final section.

METHODS

The measurements that we want to use as the basis for the study were carried out in the semi-basement space of the museum, which is located in Ljubljana. We chose a room where a large number of people are changing, but the original design of the building did not foresee this and ventilation was retrofitted in this room. The room has dimensions of 21m x 6.3m x 2.5m (Figure 1). It has ventilation with four exhaust fans installed in sets of two under the ceiling of the room, locations are marked by red crosses (Figure 1). For heating gas condensing furnace is used and there are four radiators in the room, where the parameters were measured. Locations are marked by green numbers (Figure 1). Natural ventilation is provided by twelve hopper windows of 0.75m x 0.85m on one wall and a 1.95m x 1.3m opening leading to the adjacent room.

The measurements were made over a longer period of time. For further analysis, we used data over a four-month period in spring. The experiment was carried out in the showroom during normal operation on two non-consecutive days with differrent different occupancy and ventilation modes during the heating season 2023. The natural ventilation mode was varied according to the needs, the mechanical ventilation was switched on all the time when people were present in the room. The measured parameters were CO_2, $PM_{2.5}$ and PM_{10} in relation to the amount of occupants and the ventilation during the heating season. The occupants in the room were exposed to normal operating conditions. The number of visitors varied between measurements. The temperature and relative humidity of the air were also measured. By monitoring the change curves of both concentrations, we tried to identify the correlation.

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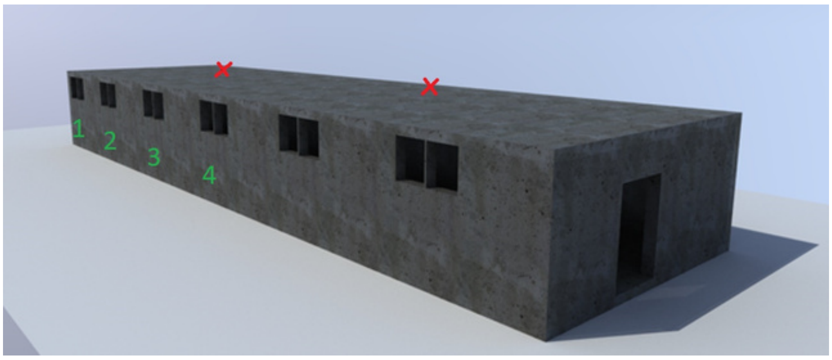

Figure 1: Model of the room in which the measurements were made

A Testo 400 sensor was used, with a CO_2 probe placed at a height of 1.6m. The measurement error of the sensor in the measurement range is ±(0.3 °C + 0.3 % of mv) for temperature measurements, ±(50 ppm + 3 % of mv) for CO_2 concentration measurements and ±(2 % RH) for relative humidity. Aerosol quantity and concentration were measured with a Grimm 11-D aerosol spectrometer at 60s intervals. The minimum counting efficiency in the measured range is 0.8. The maximum uncertainty for the magnitude in the measured range is ±(4 % nm). A Testo high precision vane probe was used to measure the air flow with a measurement accuracy of ±(0.1 m/s + 1.5 % of mv).

The maximum daily outdoor temperature on the first day was 20.4°C, while on the second day it was 9.2°C. The airborne particulate matter was 16 μg/m³ for $PM_{2.5}$ and 24 μg/m³ for PM_{10} on the first measurement day and 10 μg/m³ for $PM_{2.5}$ and 16 μg/m³ for PM_{10} on the second measurement day [16, 17].

The measured flow rate of all four outlet fans located at the centre and at the end of the room was 347 m^3/h. The number of air changes is 1.05 per hour. At the maximum occupancy of 19 persons, the air change is 18.28 m^3/h. The main opening through which the air enters the room is the door leading to the next showroom. This means that the exit air contains more pollutants than would be present if fresh outside air entered the room directly.

Experiment

The measurements were divided into two ventilation regimes.

Regime 1: 23.3.2023

Intensive natural ventilation at three intervals per day when the room was empty. In between, an average of 15 people were in the room at two intervals. Mechanical ventilation was on at all times.

The main opening through which the air enters the room is the door leading to the next showroom. This means that the exit air contains more pollutants than would be present if fresh outside air entered the room directly.

9:15-9:30	The entrance door and all the windows in the room connected to the door are wide open, and in the room where the measurements are taken, the windows are open.
9:30-10:15	There are visitors in the room, about 15 people in the room.
11:55-12:05	The entrance door and all the windows in the room connected to the door are wide open, and in the room where the measurements are taken, the windows are open.
12:05-12:55	There are visitors in the room, about 15 people in the room.

Regime 2: 5.4.2023

In the second regime, natural ventilation was carried out in accordance with monitoring the increase in CO_2 concentration in order to keep the value at an acceptable level. On this day, the room was occupied by between 16 and 19 visitors, with pauses during which intensive cross ventilation took place. Natural ventilation with the windows open was carried out at all times and cross ventilation when the room was empty. Mechanical ventilation was on at all times.

By measuring these parameters, we have confirmed that the ventilation provided in the building with its current use is inadequate and does not provide acceptable levels of pollutants in the indoor air.

8:40-8:50	Ventilation was carried out with the front door and all windows open.
9:45-9:55	Ventilation was carried out with the front door and all windows open.
10:45-10:55	Ventilation was carried out with the front door and all windows open.
11:45-11:55	Ventilation was carried out with the front door and all windows open.
13:45-14:25	Ventilation was carried out with the front door and all windows open.

RESULTS AND DISCUSSION

By measuring these parameters, we have confirmed that the ventilation provided in the building with its current use is inadequate and does not provide acceptable levels of pollutants in the indoor air. $PM_{2.5}$ levels of 32 μg/m^3 on the first and 27 μg/m^3 on the second day of measurement (Table 1) and PM_{10} levels of 57 μg/m^3 on the first and 59 μg/m^3 on the second day of measurement (Table 2) are well above the WHO recommended values, even with intensive hybrid ventilation [15].

The CO_2 concentration during the time when visitors are in the room does not provide the minimum recommended standards. The values of both measured quantities should be reduced, which would require improving the ventilation efficiency and installing better devices that would bring outside air into the space, not the air from the adjacent room. Limiting the maximum number of people in the room would likewise be helpful.

Table 1: Proportion of $PM_{2.5}$ aerosol measurements above the limit values during the period considered

$PM_{2.5}$ [μg/m³]	>15	>25	>35	Average
23.3. [%]	100	100	17	32
5.4. [%]	94	43	21	27

The values of both measured quantities should be reduced, which would require improving the ventilation efficiency and installing better devices that would bring outside air into the space, not the air from the adjacent room.

Table 2: Proportion of PM_{10} aerosol measurements above the limit values during the period considered

PM_{10} [μg/m³]	>45	>50	>60	Average
23.3. [%]	70	60	41	57
5.4. [%]	63	57	47	59

Average $PM_{2.5}$ values were 18% higher on the first measurement day. PM_{10} values were 3% higher on the second measurement day. The highest value measured on the second measurement day was 138 μg/m³.

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Table 3: Proportion of CO_2 measurements exceeding the limit values during the period considered [15]

CO_2 [ppm]	>1000	>1500	>2000	>2500
23.3 [%]	57	27	3	0
5.4. [%]	82	55	21	4

Table 4: Average CO_2 Levels

CO_2 [ppm]	Average value	Standard deviation	Range
23.3 [%]	1162	433	614 - 2060
5.4. [%]	1625	521	576 - 2612

Compared to PM values, CO_2 concentration values vary considerably more. On a day when the occupancy was lower, the values are also significantly lower. Within the acceptable range, the concentration was applied 43% of the time on the first day and 18% of the time on the second day (Table 3). The measured minimum value vas 576 ppm at the time the visitors first entered the space. Maximum value was 2612 ppm and it was measured on the second day. It can be observed that the effect of the amount of people in the room has a stronger influence on the CO_2 concentration than on the particulate concentration and that the measurements of our study show that the concentrations do not increase linearly with the amount of people in the room.

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It can be observed that the effect of the amount of people in the room has a stronger influence on the CO_2 concentration than on the particulate concentration and that the measurements of our study show that the concentrations do not increase linearly with the amount of people in the room.

The relative humidity and temperature graph of the first day meets the minimum requirements (Figure 2) and despite the increase in relative humidity with occupancy, the ventilation present is successful in maintaining the minimum value. The graph of the measurements on the second day, when the outside temperature was lower, illustrates the situation of inadequate relative humidity. At each ventilation the value falls below the minimum required. The minimum daily reading was 20.8% at the end of the long duration cross natural ventilation (Figure 2).

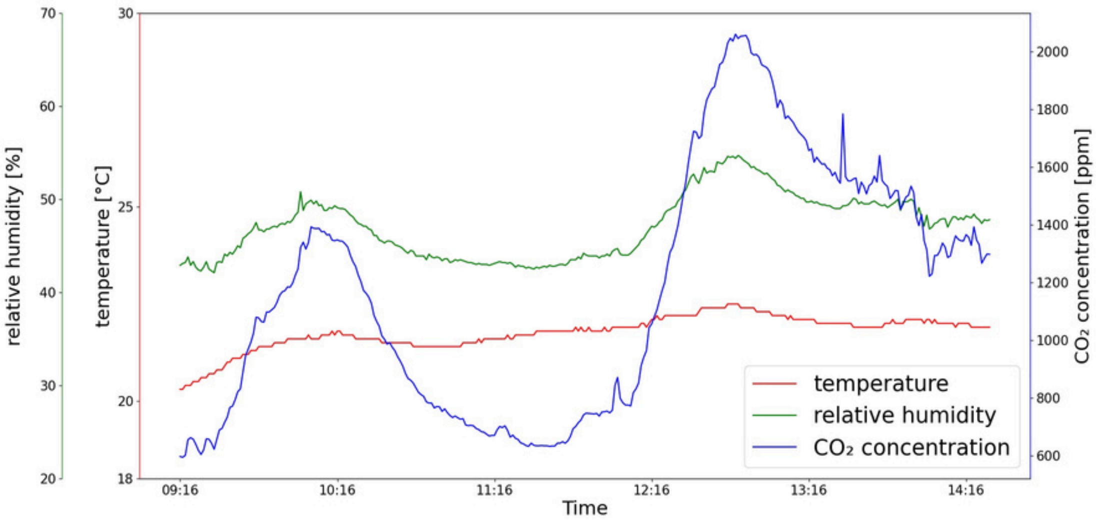

Figure 2: CO_2 concentration, temperature and RH of indoor air on 23.3.2023

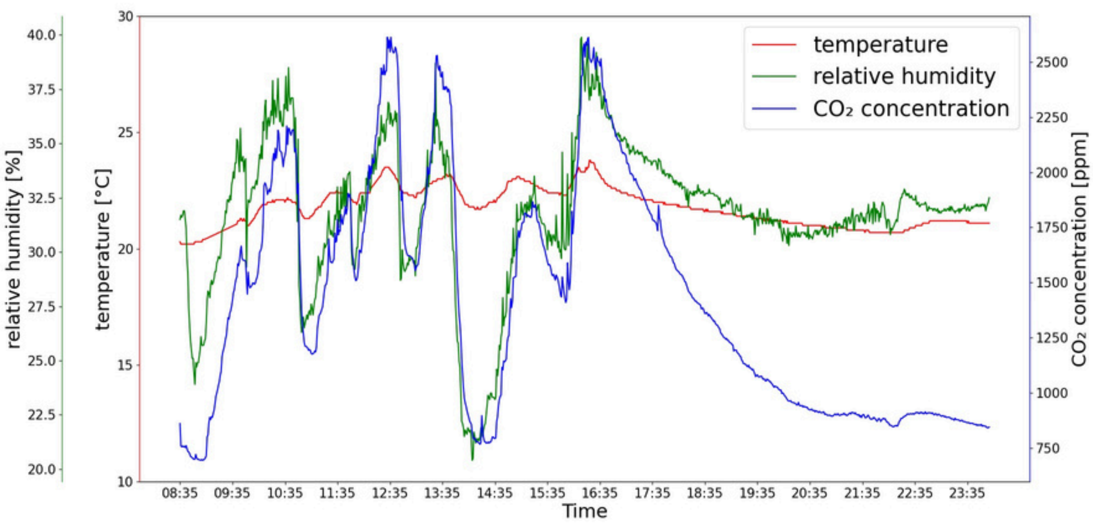

Figure 3: CO_2 concentration, temperature and RH of indoor air on 5.4.2023

From the graphs, we conclude that the concentration of 2.00 µm aerosols follows a very similar trend to that of CO_2, while the 0.65 µm aerosol curve follows this concentration more loosely, but still shows a partial pattern.

The graphs show the success of cross-flow natural ventilation in removing pollutants from rooms, but this can only be done when there are no people in the room due to draughts (Figure 4). On a day when there were more visitors in the room, the CO_2 content increased sharply, indicating that the capacity of the room is lower than the occupancy at the current ventilation capacity (Figure 4). We compared the trends of the concentration curves of aerosols of 0.65 µm and 2.00 µm. From the graphs, we conclude that the concentration of 2.00 µm aerosols follows a very similar trend to that of CO_2, while the 0.65 µm aerosol curve follows this concentration more loosely, but still shows a partial pattern. It can be argued that, under similar conditions with the same ventilation regimes, the CO_2 value is also an indicator of particulate matter in the air and thus, under these conditions, an increase in CO_2 is indicative of a general deterioration in air quality.

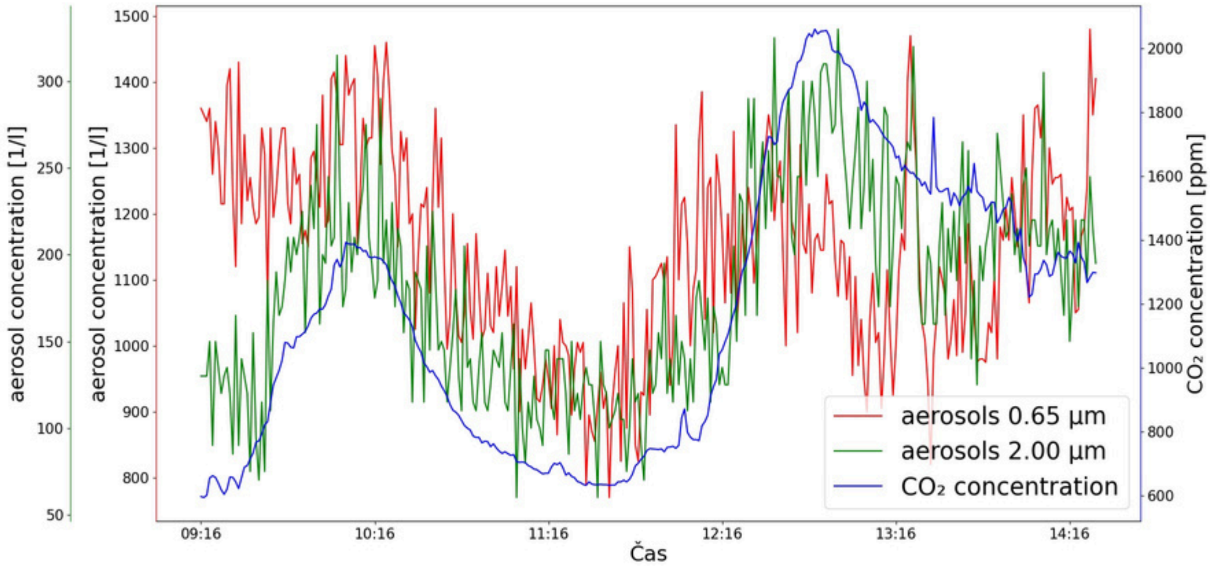

Figure 4: CO_2 and aerosol concentration of indoor air on 23.3.2023

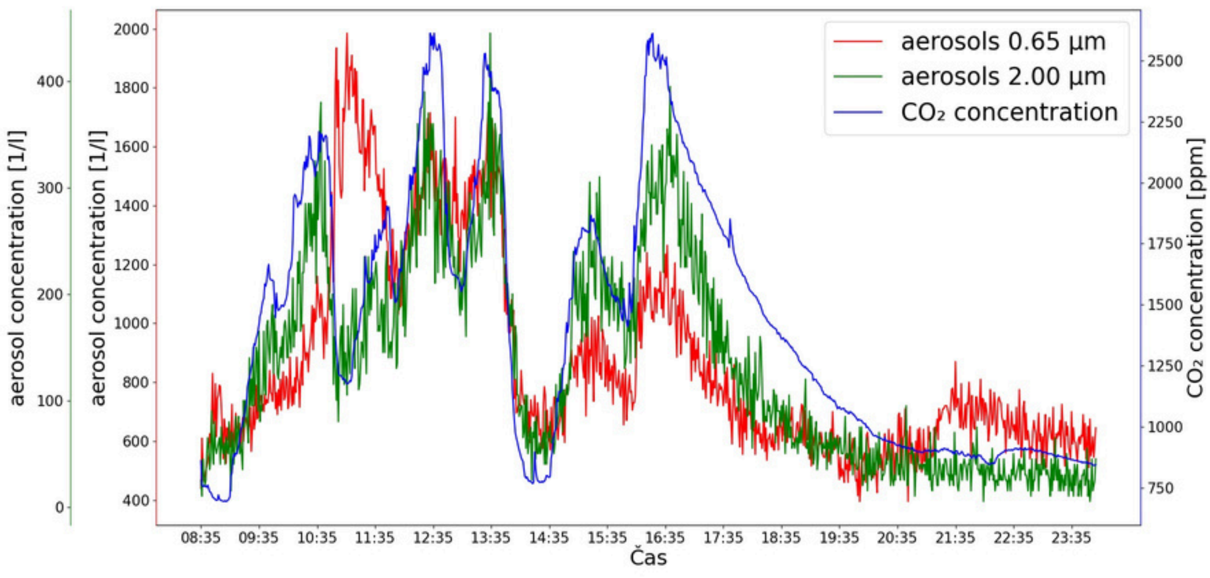

Figure 5: CO_2 and aerosol concentration of indoor air on 5.4.2023

The distribution of aerosol concentrations on the first measurement day before and during natural cross ventilation illustrates that ventilation removes most of the larger pollutants from the room and particles in range PM_1 are the most abundant in the room (Figure 6).

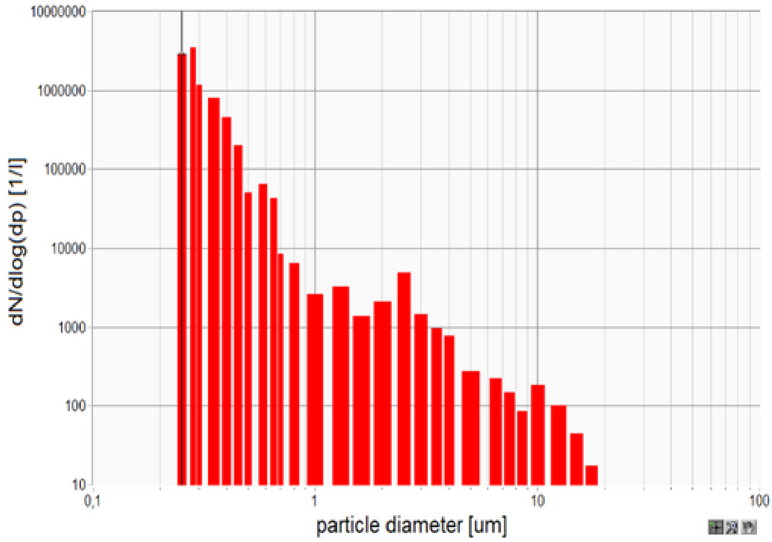

Figure 6: Particle number concentration per unit logarithmic size interval on measurement day 23.3.2023 at 10:00

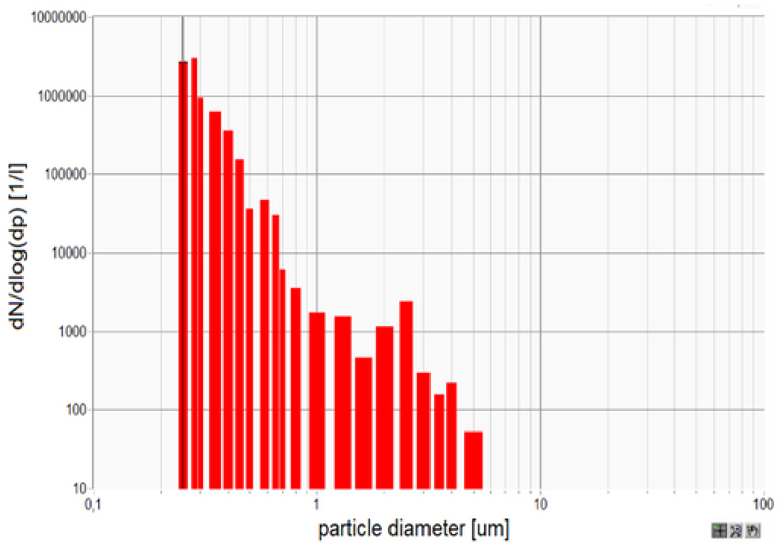

Figure 7: Particle number concentration per unit logarithmic size interval on measurement day 23.3.2023 at 11:30

Ventilation removes some pollutants from the room (Figure 7), even if it does not meet the minimum standards [15].

The findings of this study are consistent with previous research, offering similar insights into the importance of monitoring indoor air quality parameters, especially CO_2, for assessing ventilation effectiveness [6, 7, 8]. These studies collectively highlight the significance of adequate ventilation in indoor spaces for maintaining good air quality and protecting occupant health. However, they also underscore the challenges posed by inadequate ventilation and its implications for indoor air quality. Despite this alignment in findings, there remains a need for further research in diverse contexts to deepen our understanding of the relationship between ventilation effectiveness, indoor air quality, and occupant health outcomes.

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CONCLUSION

The variation in airborne particulate matter levels can be estimated from a preliminary study of the spatial variation of particulate matter in the room. This method can be used to ensure adequate air quality in the museum. The finding allows us to assess the overall air quality by simply measuring the CO_2 concentration in a room where people are the main source of pollution and to take appropriate action when the values are not satisfactory. Air quality was negatively affected by increased visitor presence and inadequate ventilation. The maximum recorded CO_2 concentration in the room reached 2612 ppm during peak occupancy with 19 visitors. The minimum CO_2 level measured was on the same day, 567 ppm. On the first day, the average CO_2 concentration stood at 1162 ppm, while on the second day, it rose to 1625 ppm. The CO_2 concentration of the air is higher when there are more people in the room. This value is also an indicator of other pollutants or aerosols emitted by people. The highest PM_{10} airborne value was 138 μg/m³, also at the highest occupancy. This means that high levels of CO_2 in the air are also indicative of high levels of particulate matter.

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We found that hybrid ventilation is more efficient than mechanical ventilation alone in the museum space, but it is still not adequate enough. A more efficient ventilation system needs to be installed in the space, and until then, based on the findings, we can limit the number of occupants to ensure adequate air quality with the current capacity.

We found that hybrid ventilation is more efficient than mechanical ventilation alone in the museum space, but it is still not adequate enough.

We analysed the indoor air quality and the impact of human presence on it. CO_2 and aerosol levels vary in a correlated manner, so just by tracking CO_2 levels we can get indirect information about aerosol levels. When CO_2 values are too high, aerosol levels in the air are also too high. However, too high values of both parameters indicate inadequate ventilation of the room. We found that an adequate indoor environment is not guaranteed if the operation of the museum is unchanged and no additional interventions are made to the building.

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In conclusion, while our study offers valuable insights into air quality and ventilation in a repurposed museum space, it may lack generalizability due to its focus on a single location. Additionally, the short duration of measurements and the absence of longitudinal data limit our understanding of seasonal variations and long-term trends. Nevertheless, our study provides a comprehensive analysis of CO_2 and particulate matter concentrations, compared against WHO guidelines. Implementing practical recommendations to enhance ventilation efficiency and optimize occupancy management represents a crucial step towards fostering a healthier indoor environment within the space investigated in our study.

Future research should address these limitations by expanding sample size, conducting longer-term measurements, and including longitudinal data to provide a more nuanced understanding of indoor air quality and ventilation dynamics.

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