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Measurements of Air Quality in Kindergartens and Schools in the Republic of Slovenia before the COVID-19 Epidemic

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This article presents measurements of air quality in school and kindergarten facilities, which were carried out in 311 spaces throughout the Republic of Slovenia, before taking measures to improve energy efficiency of measured buildings. During the measurements, the internal dimensions of the spaces were also measured, as well as data on the energy efficiency of buildings and weather data at the time of the measurements. The measurements focused on indoor carbon dioxide concentration levels and air temperature and relative humidity of indoor air. The performed statistical analysis of measurements shows a large dispersion of measured parameters in buildings, which cannot be statistically significantly related to the analyzed quantities. During the occupancy of the spaces, a statistically significant difference in the concentration of carbon dioxide in the indoor air between the spaces of schools and kindergartens was found. The results of the measurements were also evaluated from the point of view of the Corona virus disease (COVID-19) pandemic. The average value of measured carbon dioxide value during occupancy of the spaces was compared with the results of a model that predicts an airborne transmission risk. The measured average value of relative humidity in kindergartens shows that relative humidity was 37 %, where is the highest infection risk according to recent studies. The measured average carbon dioxide concentration in classrooms and playrooms significantly exceeds the safe concentration, predicted by the model, to prevent COVID-19 spread at the expected six-hour exposure.
Keywords: natural ventilation, carbon dioxide monitoring, COVID-19, indoor air quality, schools, kindergartens

Highlights

- *Indoor air quality was measured in 311 mostly naturally ventilated spaces in years 2017, 2018, 2019 and 2020, before taking measures to improve energy efficiency of measured buildings.*
- *The statistical analysis of measurements shows a large dispersion of measured parameters.*
- *Measured CO_2 concentration level in the space during occupancy does not exceed the recommendations.*
- *The results of the measurements were evaluated from the point of view of the COVID-19 pandemic with model which predicts airborne transmission risk in connection with carbon dioxide concentration level.*
- *Measured average carbon dioxide concentration in classrooms and playrooms exceeds the safe CO_2 concentration to prevent COVID-19 spread at the expected six-hour exposure.*

0 INTRODUCTION

Indoor air quality is an issue that has recently received a great deal of attention. The primary reason is the emergence of coronavirus disease, which has further highlighted the often neglected subject matter in recent years. In the past, some attention in the Republic of Slovenia has been dedicated to air quality studies. The first researches in Slovenia, which described the basic parameters of the thermal environment, were carried out in the 1990s for various types of buildings [1]. The first results of the measurements indicated that people expressed a poor sense of well-being in enclosed spaces [2]. Subsequent research [3] has confirmed that people are not happy with the indoor environment [4] to [9]. Recently, it has not been possible to find data on systematic research of the internal environment in the Republic of Slovenia. Slovenia lies a great stress on rational energy use in buildings. This directly means that recently a lot of attention has been paid to the airtightness of buildings, and less to the quality of indoor air.

In the standards and recommendations that were implemented abroad in the 1990s [10] and [11], a lot of attention was given to the amount of air. Studies conducted at the time showed that many people expressed dissatisfaction with the indoor environment [12] and [13], and that people preferred a naturally ventilated environment, or that sick building syndrome related symptoms were lower in naturally ventilated buildings [14], as was also shown in the mentioned studies carried out in the Republic of Slovenia.

Indoor air quality is also directly related to health, as people are exposed to substances in the indoor environment that can also affect health. Numerous studies show that air quality in buildings with natural ventilation can be poor, which also has a negative effect on the intellectual abilities of individuals [15] and [16]. Studies show that exposure to carbon dioxide (CO_2) in the indoor environment generally has no effect on health, but some research shows that

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exposure to low concentrations of CO_2 (1000 ppm) already has a direct impact on the cognitive abilities of individuals [17]. On the other hand, other studies, such as [18] and [19] show completely different results, which may lead to the conclusion that the results of studies of the impact of CO_2 on the cognitive abilities of individuals are quite inconsistent [20].

Humans emit into the internal environment many substances called human bioeffluents that can be exhaled and dermally emitted. Studies have shown that exhaled bioefluent can contain over 600 substances [21] and dermally emitted almost 900 [22]. In doing so, dermally emitted bioeffluents have a greater impact on the perceived indoor air quality [23].

Even before the COVID-19 pandemic, the issue of air quality in naturally ventilated school spaces was given due attention [15] and [24], and with the emergence of the pandemic, studies are also being directed from spontaneous to strategic natural window ventilation [25] which improves air quality in naturally ventilated areas.

The subject research of indoor air quality in the Republic of Slovenia focused on air quality measurements before taking measures to improve energy efficiency of measured buildings in 2017, 2018, 2019 and 2020.

1 METHODS

During the research, air quality was measured in 481 spaces located in 161 buildings in different parts of the Republic of Slovenia as shown in Fig. 1. The type of facilities that were measured were schools, kindergartens, offices, cultural facilities, sports facilities and health facilities. This article presents only measurements in the spaces of kindergartens (playrooms) and schools (classrooms). In total, air quality was measured in 311 school and kindergarten spaces, 218 of which were school spaces and 93 kindergarten spaces. As part of the research, 24- or 48-hour monitoring of randomly selected spaces in the building was performed.

Measurements were performed in four sets. Table 1 shows the basic data on the time course of measurements in the performed terms.

During the measurements, three spaces were generally measured in each building. Monitoring was carried out on single place in the space throughout the period of measurements. Measurement equipment measured CO_2 concentration in the air in the space, the temperature of the air in the space and the relative humidity of the air in the space. Data was acquired every 60 seconds. The measuring accuracy of the measuring equipment used for measurements of CO_2 concentration was ±(5 % of the measured value +50 ppm) in the measuring range from 0 ppm to 9999 ppm, measuring accuracy of the air temperature was ±0.6 °C in the measuring range from –10 °C to 60 °C and measuring accuracy of the relative humidity was ±3 % in the range of 10 % to 90 % or ±5 % in the range of <10 % and >90 % respectively. Measurements were made in different annual seasons (winter, spring). For each space, data on the internal dimensions of the space was also obtained with accuracy ±0.05 m.

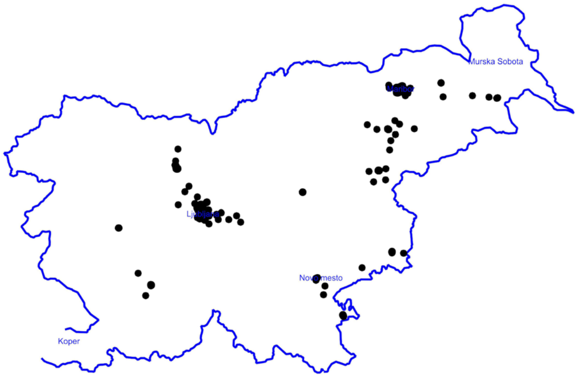

Fig. 1. *Locations of objects that were included in the measurements*

Table 1. *Sets of air quality measurements*

Set	Term of measurement
1.	2017-03-07 to 2017-04-19
2.	2018-03-24 to 2018-05-16
3.	2018-12-11 to 2019 -06-20
4.	2020-02-10 to 2020-03-13

After the measurements, the basic indicators of the measured parameters in the space during occupancy were calculated. Due to the way the space was used, the occupancy time was defined between 8 am and 12 noon for schools and between 8 am and 2 pm for kindergartens. In the case of 24-hour measurements, the average value was calculated for one day of measurements, and for 48-hour measurements, the average value represents the average for both days of measurements. Also, typical weather data for the selected measurement period were related to the weather data for the Ljubljana Bežigrad weather station, where the average value of air temperature at 2 m was taken as a reference, namely the average and the minimum value of outside air temperature at the time of measurements. Data on the energy efficiency of buildings were also obtained from public records.

2 RESULTS AND DISCUSSION

Table 2 shows the basic data of the measured spaces. Of the 311 spaces analyzed, only 9 spaces were mechanically ventilated. Fig. 2 shows the average outdoor air temperature (T_AVER) and the minimum outdoor air temperature (T_MIN) at the height 2 m at the meteorological station Ljubljana Bežigrad during all four sets of measurements on the day of installation of the measuring device. From the Fig. 2 it could be seen that the majority of measurements were performed during the heating period.

Table 2. *Basic data of measured spaces*

	School	Kindergarten	Sum
Natural ventilation	215	87	302
Mechanical ventilation	3	6	9
Sum	218	93	311

Table 3 shows the measured internal average air temperature during occupancy (*t*), the measured internal relative humidity (RH) in the space during occupancy and the calculated standard deviation for both parameters. The measured average air temperature is slightly higher in kindergartens, while the RH is slightly lower. The measured values are in accordance with RH values as defined by existing building regulations design criteria for humidity in Europe (20 % < RH < 70 % per EN 16798-1 [27]). The COVID-19 epidemic has also stimulated research of the impact of the RH on the spread of the virus. The impact of RH on infection risk was found to be dependent on the ventilation rate and the size range of droplets [28]. It was found that within the RH range of 20 % to 53 % the highest mean and maximum infection risk was always seen at an RH of 37 %, while it was lower at different levels of RH. Measured values of relative humidity in playrooms in kindergartens show that RH was exactly 37 %, at the highest infection risk.

Table 3. *Measured average temperature and relative humidity in spaces*

	Schools	Kindergartens
t [°C]	22.4	22.6
STDEV t [°C]	1.29	1.02
FI [%]	42.0	37.1
STDEV FI [%]	8.94	7.43

Table 4 shows the maximum of measured CO_2 concentration in indoor air during measurements by ventilation type. As expected, higher maximum

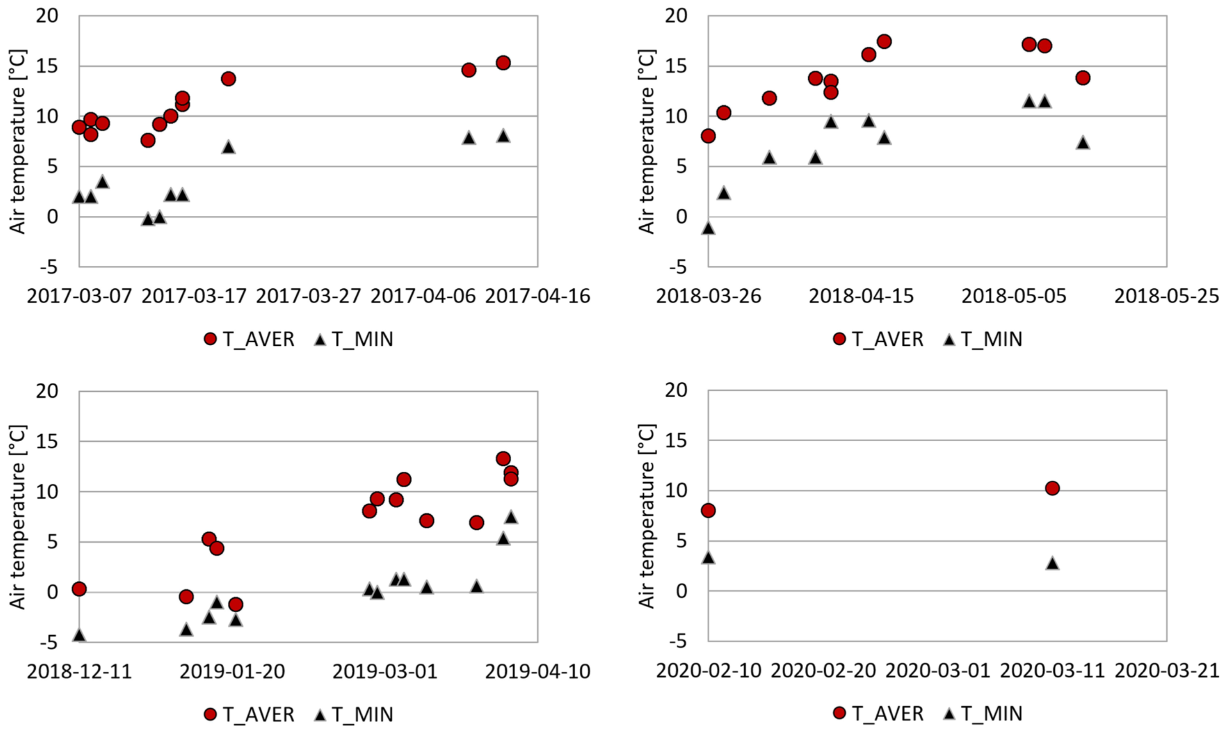

Fig. 2. *Outdoor air temperature during measurements* [26]

concentrations of CO_2 in indoor air were measured in naturally ventilated buildings.

Table 4. *Measured maximum CO_2 concentration in ppm*

Ventilation type	Maximum CO_2 concentration	
	Schools	Kindergartens
Natural ventilation	5179	3494
Mechanical ventilation	2190	2866

Fig. 3 shows the relationship between the average of measured CO_2 concentration in the spaces during occupancy of the spaces and the specific annual energy for heating obtained from the Energy performance certificates (EPC). EPC for 264 spaces was issued on the measured rating system basis, for 24 spaces EPC was issued by the calculated rating, for 24 spaces there was no EPC available in public records. Fig. 3 shows that the average of measured concentration CO_2 level during occupancy was lower in buildings with higher energy use than in buildings with lower energy use, which can be related to the airtightness of buildings. In more energy-efficient buildings, especially schools, the measured average CO_2 concentration is generally higher.

Fig. 4 shows the scatterplot of the maximum measured CO_2 concentration in indoor air and the average outdoor air temperature during measurements with marked types of facilities and type of ventilation system (natural, mechanical). It can be concluded that there is no clear relationship between the maximum measured CO_2 concentration and the average outdoor air temperature during measurements. Fig. 5 similarly shows the scatterplot of the maximum measured CO_2 concentration in the indoor air and the minimum average outdoor air temperature during measurements with the indicated types of facilities and ventilation type. It can be concluded that there is again no clear connection between the maximum measured CO_2 concentration and the minimum outdoor air temperature during measurements.

Figs. 6 and 7. show the relationship between the average measured CO_2 concentration during occupancy of the spaces and the average and the minimum outdoor air temperature. It can be concluded that there is also no clear connection between the measured average CO_2 concentration during occupancy and the average or minimum outdoor air temperature.

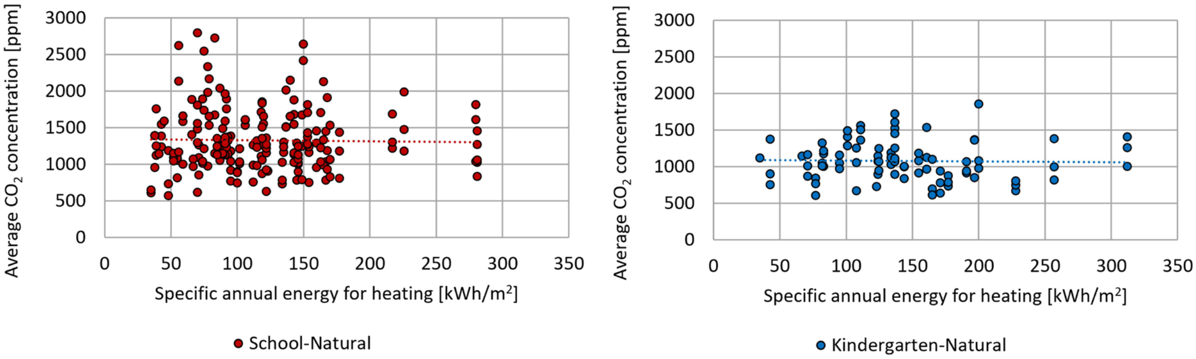

Fig. 3. *Scatterplot of average CO_2 concentration vs specific annual energy for heating*

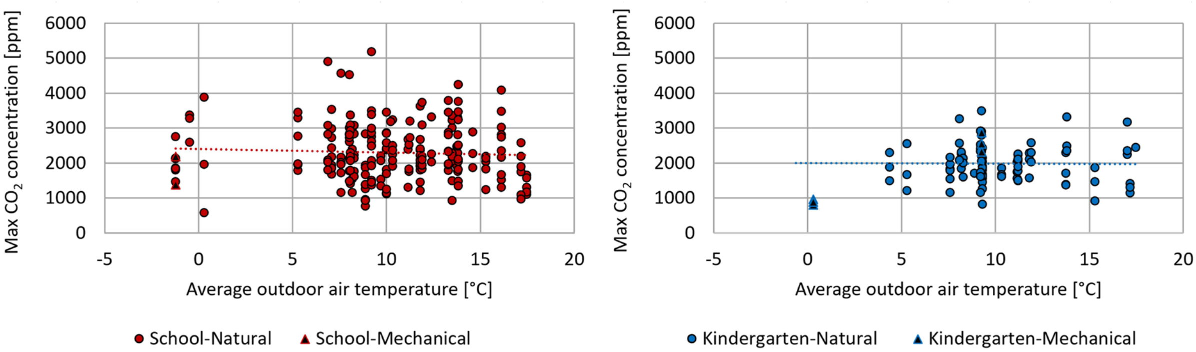

Fig. 4. *Scatterplot of maximum CO_2 concentration vs average outdoor air temperature*

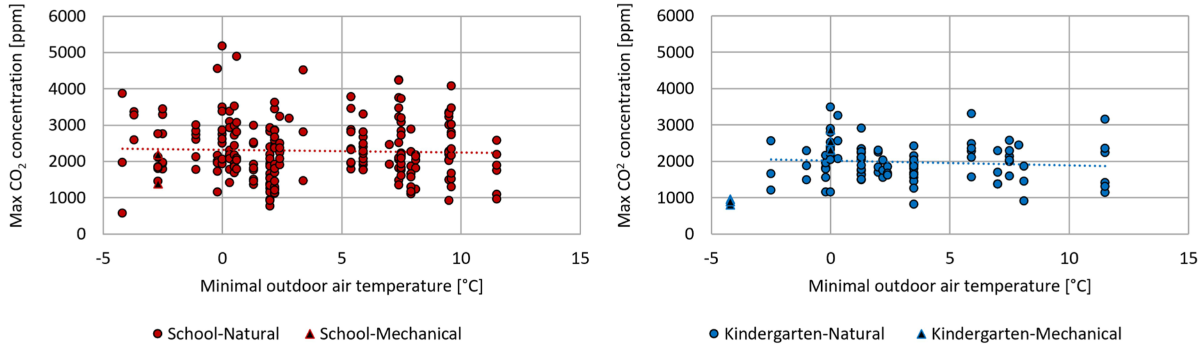

Fig. 5. *Scatterplot of maximum CO_2 concentration vs minimal outdoor air temperature*

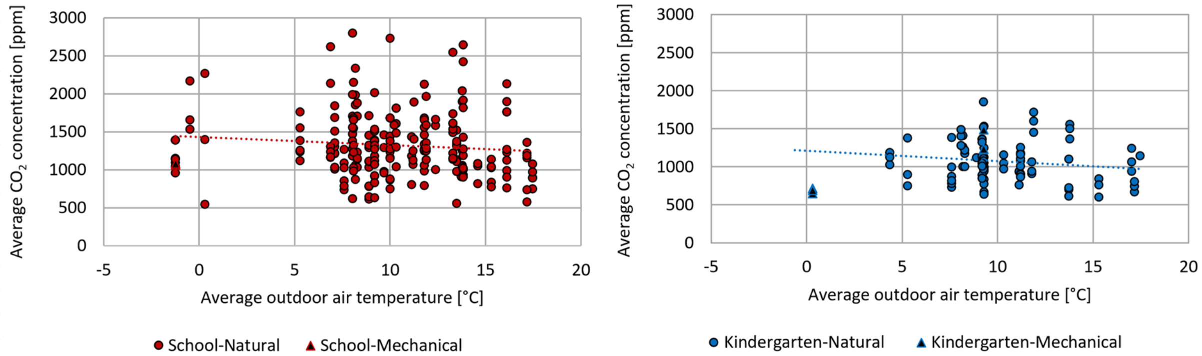

Fig. 6. *Scatterplot of average CO_2 concentration vs average outdoor air temperature*

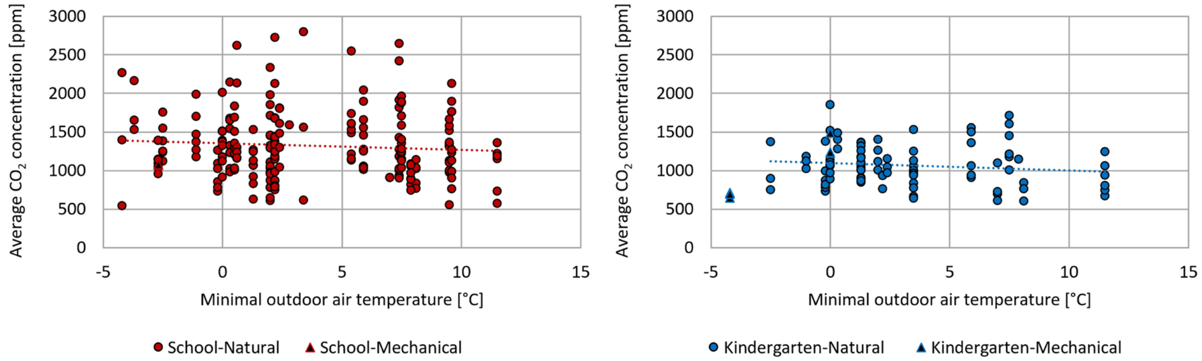

Fig. 7. *Scatterplot of average CO_2 concentration vs minimum outdoor air temperature*

From the above it can be concluded that the weather conditions do not have a major impact on the indoor air quality. Table 5 shows the average value of the measured maximum concentrations for all spaces ($CO_{2,\ max}$), the standard deviation of the measured maximum concentrations, the average value of the measured average concentrations during occupancy ($CO_{2,\ ave}$) and the standard deviation of the measured average CO_2 concentrations during occupancy in spaces. The data show that the average value of measured CO_2 concentrations is highest in naturally ventilated school buildings. The calculated standard deviation, however, indicates a similar dispersion in all buildings, regardless of the type of building or the method of ventilation. The table also shows that a lower CO_2 concentration was measured in mechanically ventilated spaces (School Mechanical, Kindergarten Mechanical), which cannot be confirmed statistically significantly due to the sample size (only 9 mechanically ventilated spaces).

Table 5. *Average value of measured maximum CO_2 concentrations in ppm*

	$CO_{2,max}$	STDEV $CO_{2,max}$	$CO_{2,ave}$	STDEV $CO_{2,ave}$
School Natural	2277	829	1310	442
School Mechanical	1789	843	1072	450
Kindergarten Natural	1979	843	1068	450
Kindergarten Mechanical	1732	838	1001	449

Analysis of variance (ANOVA) is a type of analysis that tests the difference among means of different groups [29]. The analysis performed, where we tested the null hypothesis that the measured maximum concentration and the measured average CO_2 concentration during occupancy are the same in schools and kindergartens, shows a statistically significant difference, so we can say that the measured CO_2 concentration in kindergartens was different from the measured CO_2 concentration in schools (Tables 6 and 7).

Table 6. *Analysis of variance for the maximum measured CO_2 concentration*

	Between Groups	Within Groups	Total
Sum of Squares	7086267	1.66E+08	1.73E+08
df	1	306	307
Mean Square	7086267	543580.5	
F	13.0363		
Sig.	0.000357		

Analysis of variance shows also that there is a statistically significant difference between the volume of measured spaces in schools and kindergartens. The average volume of schoolroom was 189.3 m^3, and the average volume of playroom in the kindergarten was 138.1 m^3. Analysis of variance shows that there is a statistically significant difference between the area of spaces in schools and kindergartens. The average area of the school space was 56.2 m^2, and the average area of the kindergarten space was 44.7 m^2. There is also a statistically significant difference between the height of spaces in schools and kindergartens. The average height of the school space was 3.36 m, and the average height of the space in the kindergarten was 3.08 m. Figs. 8 to 10 show the relationship between the average measured CO_2 concentration during occupancy and the dimensions of the measured spaces. Figures shows that there is again no clear relationship between the volume, area or height of the space with the measured average concentration of CO_2 during occupancy in the space.

Table 7. *Analysis of variance for the average value of the measured CO_2 concentration during occupancy*

	Between Groups	Within Groups	Total
Sum of Squares	4279101	45153467	49432568
df	1	306	307
Mean Square	4279101	147560.4	
F	28.999		
Sig.	1.45E-07		

In the period since the outbreak of the COVID-19 pandemic, special attention has also been given to the possible links between CO_2 concentrations and the risk of virus exposure, based on the finding that CO_2 concentrations are a measure of pathogens in the internal environment, which enables use of Wells-Riley model for determination of airborne transmission in an indoor space that is well-mixed [30]. Various models have also been developed that describe infection risk based on CO_2 level for typical indoor environments [31] and [32], where special attention was given to evaluate critical time spent in a space with infected person. Based on the models, a guideline to limit indoor airborne transmission of COVID-19 was developed [33], with an online

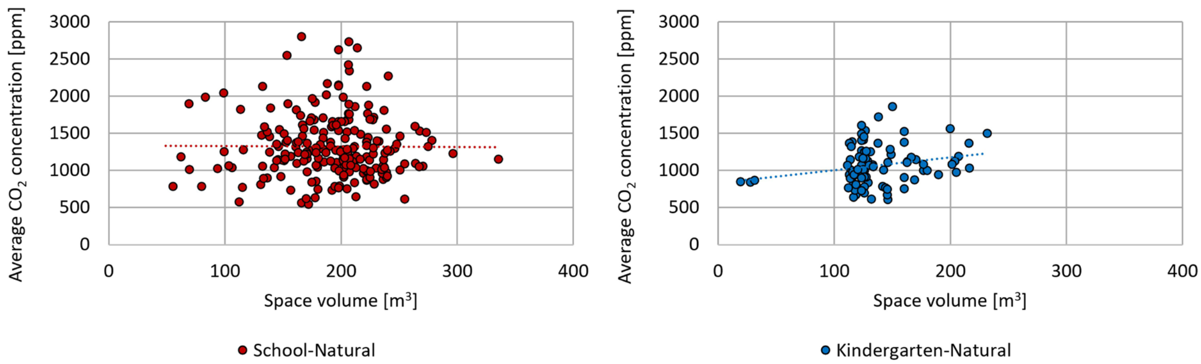

Fig. 8. *Scatterplot of average CO_2 concentration vs space volume*

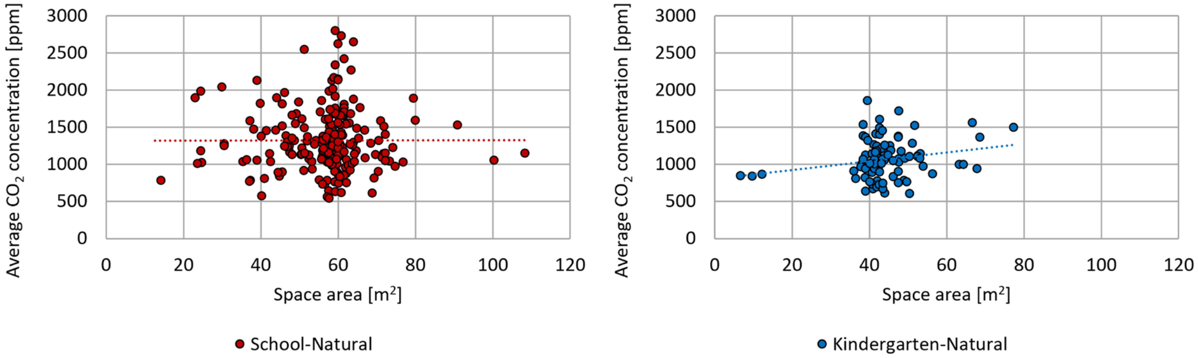

Fig. 9. *Scatterplot of average CO_2 concentration vs space area*

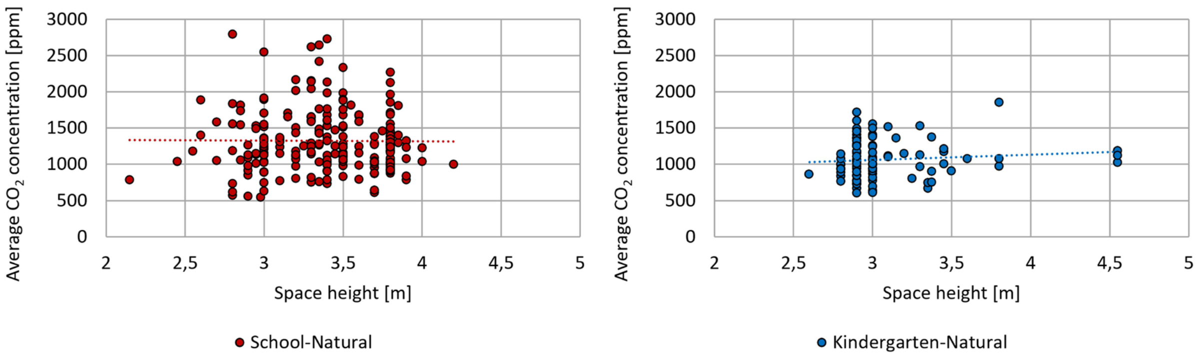

Fig. 10. *Scatterplot of average CO_2 concentration vs space height*

evaluation application [34]. The model [33] predicts airborne transmission risk from the real-time CO_2 measurements. This model was used to evaluate our measurement results where we evaluated the possibility of virus spread to populations under 15 years of age.

If we take into account the parameters collected in Tables 8 and 9 in the model, in the case when users do not wear masks in school spaces, we can find COVID-19 transmission for Delta variant of virus occurs after 19 min, and in the case of Omicron variant after 14 min. If users wear properly installed masks with an efficiency of 90 %, the prediction of the model indicates that the transfer of COVID-19 with Delta variant of virus occur after 4 hours, and in the case of Omicron variant of virus after 3 hours.

Table 8. *Basic input parameters for model [33] from measurements*

	School	Kindergarten
Area [m²]	56.2	44.7
Height [m]	3.36	3.08
RH [%]	42	37.1
$CO_{2,ave}$ [ppm]	1310	1068
Persons in the space	28	22

The model predicts also the safe concentration of CO_2 at the assumed activity. In the case of the Delta variant of virus, if we do not wear masks, the safe CO_2 concentration for six hours of exposure is 837 ppm, and in the case of the Omicron variant of virus, this limit is 792 ppm. This means that the measured average concentration of 1310 ppm significantly exceeds the safe concentration of CO_2 as a measure of possible COVID-19 virus transmission. However, if users wear properly fitted masks with an efficiency of 90 %, the model predicts that a safe CO_2 concentration for six hours of virus exposure is more than 2000 ppm, regardless of the virus variant. This means that the measured average concentration of 1310 ppm is lower than the recommended one for six hours of exposure.

If we take into account the parameters collected in Table 9 in the model with the data for total floor area and ceiling height, represented in Table 10 for kindergartens, we can find that COVID-19 transmission with Delta variant of virus occurs after 18 min, and in the case of Omicron variant of virus after 13 minutes. If there were only 10 users instead of 22 in the same space, then the COVID-19 transmission with Delta variant occurs after 29 minutes, and in the case of the Omicron variant of virus after 22 minutes. Both results were calculated for the case when users do not wear masks in kindergarten spaces.

Table 9. *Basic input parameters for model [33] for school*

Parameter	Without mask	With mask
Total floor area [m^2]	56.2	56.2
Average ceiling height [m]	3.36	3.36
Ventilation [h^{-1}]	0.3	0.3
Recirculation rate [h^{-1}]	0	0
Filtration system (MERV)	0	0
Relative humidity [%]	42	42
Breathing flow rate [m^3/h]	0.49	0.49
Infectiousness of exhaled air [quanta/m^3]	72	72
Mask efficiency	0	0.9
Mask fit	0	0.95
Risk tolerance	0.1	0.1
Age group	0.23	0.23
Viral strain for Delta variant	2.5	2.5
Viral strain for Omicron variant	4	4
Percentage immune	0	0
Effective aerosol radius (at RH = 60 %) [μm]	2	2
Maximum viral deactivation rate [h^{-1}]	0.6	0.6
Outdoor air fraction	1	1
Aerosol filtration efficiency	0	0
Effective aerosol radius (at RH = 60 %), [μm]	2	2
Mask passage probability	1	0.145
Prevalence	0	0
Percentage susceptible, ps	1	1
Age factor	0.23	0.23

Table 10. *Input parameters for model [33] for kindergarten*

Parameter	Without mask
Total floor area [m^2]	44.7
Average ceiling height [m]	3.08

As it was already mentioned, the model also calculates the safe concentration of CO_2 at the assumed activity. In the case of the Delta variant of virus and if masks are not used, the safe CO_2 concentration for six hours of source exposure is 951 ppm, and in the case of the Omicron variant of virus this limit is 914 ppm. This means that the measured average concentration of 1068 ppm significantly exceeds the safe concentration of CO_2 as a measure of possible COVID-19 virus transmission at six-hour exposure.

4 CONCLUSIONS

In our research, which was conducted before the COVID-19 pandemic, we focused on the indoor air quality in school and kindergarten facilities and tried to connect it with selected facility parameters. It turns out that the dispersion of measured parameters in buildings is large and that there is no statistically significant relationship between measured parameters, selected facilities parameters and the energy efficiency of the building. Due to the small sample of mechanically ventilated spaces, it cannot be statistically significantly stated that the air quality parameters in mechanically ventilated spaces are better, but the results clearly show that both the maximum value and the average value during occupancy are lower in mechanically ventilated spaces than in naturally ventilated spaces. We proved that the measured maximum as well as the measured average CO_2 concentration during the time of occupancy is statistically significantly different between kindergarten and school spaces. All this shows the great influence of the users of the spaces on the air quality in them or in other words: the users of naturally ventilated spaces are the ones who have to take care of the air quality in the buildings. This is often difficult without the help of special devices or sensors, as the user of the space adapts to the air quality when one is indoors for a long time.

The results were also analyzed in the light of the COVID-19 pandemic. It was found that the measured average relative humidity in kindergartens at the time of occupancy was 37.1 %, where the maximum infection risk occurs. Analysis of the measured average CO_2 concentration during occupancy in schools with prediction of the model which predicts airborne transmission risk shows that the measured average concentration in classrooms at 1310 ppm significantly exceeds the safe level of CO_2 concentration as a measure of COVID-19 virus transmission at six-hour exposure, for Delta or Omicron variant of virus if users don't wear masks. However, if users wear properly installed masks with an efficiency of 90 %, the model's prediction shows that the safe CO_2 concentration for a six-hour exposure is more than 2000 ppm, regardless of the virus variant. The analysis of the measured average concentration of CO_2 in kindergartens shows that the measured average concentration in playrooms with 1068 ppm also significantly exceeds the safe concentration of CO_2 as a measure for the transmission of COVID-19 virus at six hours of exposure, for Delta or Omicron variant of virus if users don't wear masks.

All of the above shows that naturally ventilated spaces are ventilated relatively stochastically. Although the measured air quality in buildings, before taking measures to improve energy efficiency of buildings, does not exceed the recommendations from the point of view of CO_2 concentration in the space, in light of the COVID-19 pandemic in naturally ventilated buildings it is necessary to ensure adequate ventilation with help of appropriate sensors.

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