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Indoor Climate Performance in a Renovated School Building

Pavla Mocová [1,*] and Jitka Mohelníková [2]

[1] Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemedelska 3, 613 00 Brno, Czech Republic
[2] Faculty of Civil Engineering, Brno University of Technology, Veveri 331/95, 602 00 Brno, Czech Republic; mohelnikova.j@fce.vutbr.cz
* Correspondence: pavla.mocova@mendelu.cz; Tel.: +420-7376-24371

Abstract: Indoor climate comfort is important for school buildings. Nowadays, this is a topical problem, especially in renovated buildings. Poorly ventilated school classrooms create improper conditions for classrooms. A post-occupancy study was performed in a school building in temperate climatic conditions. The evaluation was based on the results of long-term monitoring of the natural ventilation strategy and measurements of the carbon dioxide concentration in the school classroom's indoor environment. The monitoring was carried out in an old school building that was constructed in the 1970s and compared to testing carried out in the same school classroom after the building was renovated in 2016. Surprisingly, the renovated classroom had a significantly higher concentration of CO_2. It was found that this was due to the regulation of the heating system and the new airtight windows. The occupants of the renovated classroom have a maintained thermal comfort, but natural ventilation is rather neglected. A controlled ventilation strategy and installation of heat recovery units are recommended to solve these problems with the classroom's indoor environment. Microbiological testing of the surfaces in school classrooms also shows the importance of fresh air and solar radiation access for indoor comfort.

Keywords: building renovation; indoor environment; indoor climate comfort; indoor air; natural ventilation; CO_2 concentration

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1. Introduction

The indoor climate in buildings is influenced by the ventilation strategy and air change in rooms. A fresh air supply is crucial for a healthy indoor environment, especially in highly occupied rooms [1]. If non-ventilated, enclosed spaces are exposed to an increased concentration of metabolically generated carbon dioxide emissions [2] from the occupants' breathing. A low carbon dioxide concentration is an indicator of the indoor air's freshness. This depends on a proper ventilation strategy. Insufficiently ventilated buildings evince sick building syndrome [3,4]. The symptoms assessed for the syndrome are related to respiratory tract problems, headache, fatigue and difficulty concentrating [5,6].

Poor ventilation in buildings has a negative effect on the occupants' health. Sufficient ventilation is important for indoor climate comfort, especially in school buildings [7–10]. The ventilation conditions in classrooms were studied with respect to providing convenient conditions [11,12] for students' activities in an indoor environment [13]. It has been proven that improper ventilation can enhance children's health problems, especially respiratory symptoms, as shown in [14]. A phase study in childcare centres confirmed that indoor air quality is associated with disposition for asthma diagnoses [15]. Ventilation rates also play an important role in pupils' learning performance [16–24] and students' academic achievements [25]. The positive effect of ventilated schoolrooms on the reduction in absence due to illness was also discovered in these studies [26,27]. Heating, ventilation and cooling (HVAC) strategies are important for a school building's indoor climate [28–30]. Efficient HVAC systems could solve fresh air supply problems indoors, but, on the other hand, they present a high demand for energy consumption as well as installation and service investment compared to natural ventilation.

Natural ventilation systems remain convenient design solutions for energy efficient and sustainable buildings to maintain indoor comfort conditions [31]. Primarily in schools, natural ventilation has high importance for indoor air comfort [32,33]. In naturally ventilated schools, the air change rate is based on the manual airing of classrooms through windows and doors. The effect of the natural ventilation strategy on the indoor air quality in classrooms was evaluated [34,35]. The performance of naturally ventilated classrooms under various outdoor conditions during heating season was studied using CFD simulations [36]. All of the above-mentioned findings show the importance of indoor air quality, which must be controlled in newly constructed as well as renovated buildings.

For new buildings, design requirements for indoor climate comfort are specified [37–39]. In existing buildings, post-occupancy monitoring of the real indoor conditions represents a convenient way to control the internal environment. Monitoring of school buildings for ventilation and indoor climate comfort was provided for naturally ventilated spaces as well as for spaces with HVAC design strategies [30,40]. The measurements showed that high CO_2 concentrations are not uncommon in classrooms where the principal source of ventilation is manually operated windows [40]. A controlled ventilation schedule appears to be a convenient strategy for school classrooms' indoor air quality.

The current trends in indoor comfort in schools across countries within the European Union show potential for harmonised design criteria and recommendations. The European Commission's project Sinphonie (Schools Indoor Pollution and Health: Observatory Network in Europe) [41] is focused on the establishment of a scientific and technical network to act at the EU level with the long-term objective of improving the air quality in schools and kindergartens. Efforts are focused on reducing the risk of respiratory diseases among children and teachers due to outdoor and indoor air pollution. At the same time, the project supports future policy actions by formulating guidelines, recommendations and risk management options for better indoor air quality and the associated health benefits in schools.

The Sinphonie was the first Europe-wide pilot project to aim at monitoring the school environment and children's health across 23 European countries [41]. Sinphonie provides standardised methodologies and tools for creating better indoor climates within schools and assessing the health risks to school children and staff. A key part of the project's output is the guidelines for healthy environments within European schools [42].

The Sinphonie project also targeted the monitoring procedures of the microbial climate in schools. The study included surveys of school grounds, buildings and chosen classrooms, including indoor and outdoor air sampling, to measure a number of key pollutants and parameters recognised as important for indoor air quality by WHO guidelines [43]. The project provided a basis for the future development of guidelines on indoor biological contaminants by establishing an extensive dataset of biological compounds measured using molecular methods in a large number of classrooms in schools across Europe [41,42].

Indoor air microbial purity is highly important [44–46] for all buildings, particularly for hospitals and healthcare centres but also for schools. The existence of fungi in indoor air has been studied since the 19th century [47]. Airborne bacterial and fungal growth inside buildings is a result of human activity together with the poor ventilation that is associated with a damp indoor environment [45,48]. A relationship between fungal growth and atmospheric temperature and humidity was proven [48].

Airborne bioaerosols can contaminate indoor air and cause serious medical problems for the occupants [46]. Indoor air of high quality with regard to airborne biological particles is fundamental for convenient indoor conditions that aid the prevention of nosocomial infections, respiratory disorders and other adverse health effects such as infections, hypersensitivity pneumonitis and toxic reactions [49,50]. The influence of environmental microorganism exposure on children's asthma has been documented [51]. The indoor concentration of bacteria and fungi increases with the rate of occupancy, as studied in school classrooms [52,53]. Nevertheless, each building has its own 'background' fungal concentration that is determined by the location, building age and construction type as well as maintenance and interior design [54].

The monitoring of indoor air quality and microbial testing in buildings appears to be a convenient way of controlling the comfort of the indoor environment. This article is focused on a post-occupancy evaluation of indoor air quality and microbial testing in school classrooms. An old school building was selected for the evaluation. The building is a representative of the traditional school buildings that urgently need renovation. The building's indoor climate was monitored for one year in its former state and compared with the indoor air conditions in the school building after its renovation. The school's indoor climate evaluation was included in a research project that focused on advanced materials, structures and technologies and in a university sustainable development collaborative programme.

2. Methods

2.1. School Building Performance

In agreement with the current trends focused on indoor air quality in school buildings, a post-occupancy evaluation of a representative traditional school building was performed. Long-term monitoring of the carbon dioxide concentration in the school's classrooms as well as indoor and outdoor temperature measurements were provided. The study was carried out in a selected classroom in the building before renovation and compared with the renovated classroom. The classroom's airtightness, ventilation strategy and occupancy were controlled and compared with the requirements for optimal indoor climate conditions. Microbial testing of the classroom's surfaces was also performed.

A representative traditional school building was selected for the evaluation. The school is located in the town of Mimoň, latitude 50.659 N, longitude 14.724 E, altitude 285 m [55]. The two-floor building was constructed in the 1970s. The school building has a solid brick masonry structural system with reinforced floor structures and a flat roof with bituminous felt waterproofing.

The building was renovated in 2016. The renovation was mainly aimed at the thermal insulation of the external walls and roof as well as a window retrofit and refurbishment of the heating system. Old wooden frame windows were replaced by new ones with plastic frames and triple glazed units. The renovated building has an additional thermal insulation façade with 150 mm thermal insulation, a new roof construction with 200 mm insulation and new waterproofing membranes. A new regulated heating system was installed, and renovation of the water supply circuit was carried out. All internal spaces in the educational part of the school are naturally ventilated through windows. Only workshops and the kitchen have mechanical ventilation.

The school's classrooms are located in the east wing of the educational campus, as shown in Figure 1. One of the classrooms was selected for the evaluation. The classroom, with floor dimensions of 8.66 m × 5.3 m and a headroom height of 2.855 m, is shown in Figure 2. The classroom has three big windows; each window has an area of 1.93 m^2. All windows are oriented to the south. Monitoring the CO_2 concentration in the classroom's air together with indoor/outdoor temperature measurement and microbial testing of the classroom surfaces were the main tasks of the post-occupancy evaluation. The school classroom's performance was analysed in both its former and renovated states, as shown in Figure 3.

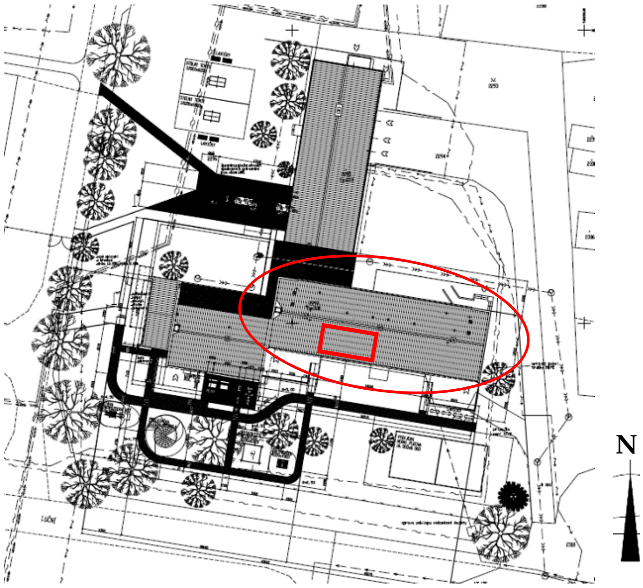


Figure 1. Situational layout of the school campus location.

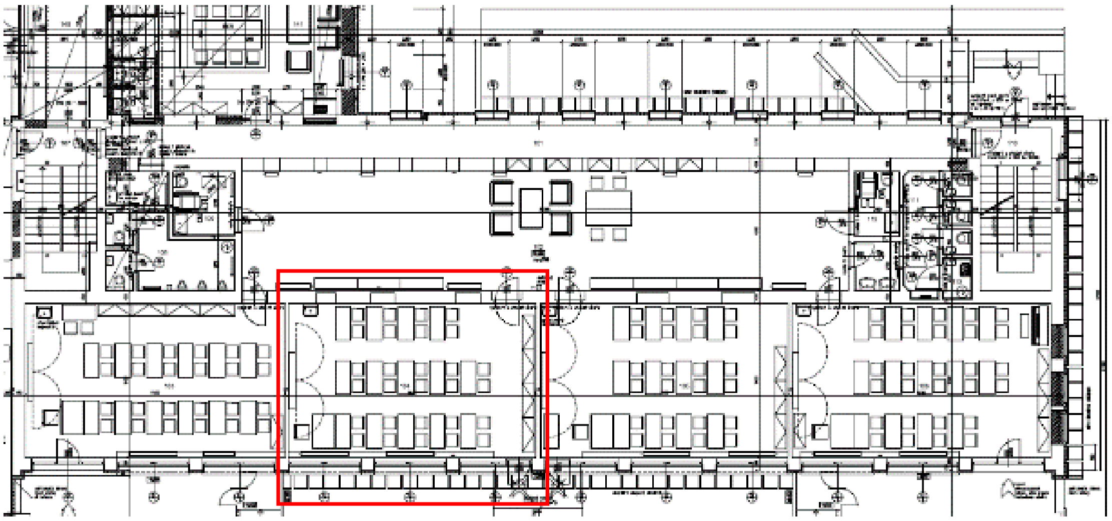


Figure 2. Part of the plan of the ground floor of the east wing of the school building with the studied classroom.

Former building	Renovated building
South facade of the east wing building	
	
Flat roof, plastered solid brick masonry walls, wooden frame and windows with double glass panes.	Thermally renovated facade and roof, and plastic windows with low-emissivity triple glass units.

Figure 3. *Cont.*

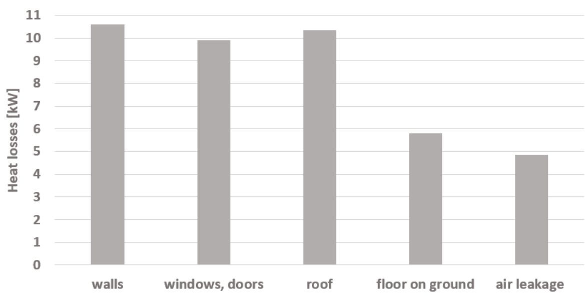
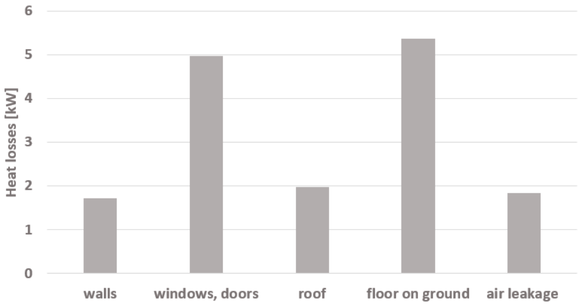
View into the classroom	
 Traditional interior of the classroom, window view is limited because of permanent shading blinds—obstruction for day-light but low shading effect for direct solar radiation.	 Classroom interior for student teamwork, windows with an undisturbed view, visual comfort, shading blinds are activated just for time of excessive solar gains.
Classroom window	
 Old wooden frame window with the shading blind. Poor thermal insulation, air leakage.	 New window with triple glazed unit and plastic frame. High airtightness and better thermal insulation.
Total energy consumption of the school building, CO_2 emissions from energy consumption	
Energy consumption 271 GJ/year, CO_2 emissions 31.67 t/year	Energy consumption 105.8 GJ/year, CO_2 emissions 12.62 t/year
Heat losses of the school building	
	

Figure 3. Photographs of the east wing of the school building campus with the classroom in its former and renovated states.

2.2. Monitoring of CO_2 Concentration

The concentration of carbon dioxide in indoor air is one of the indoor comfort parameters. An increased concentration of CO_2 in the body leads to its weakening. It influences a person's mental condition and study concentration and, as a final consequence, it could induce headache and faintness. In poorly ventilated occupied school classrooms, students are less motivated to study.

A study aimed at school children exposed to indoor CO_2 concentrations higher than 1000 ppm showed a significantly higher risk of dry cough and rhinitis (654 children in 46 classrooms), but the outdoor air flow rate per person was inversely correlated with the indoor CO_2 concentration. An increase in the indoor CO_2 concentration (range: 1000–2000 ppm) in 45 day care centres was significantly associated with reports of wheezing in the 3186 attending children, and a positive trend was observed between the CO_2 concentration and the prevalence of asthma [56].

The requirements for indoor air quality are included in design and standard recommendations [37–39]. In technical documents, acceptable concentrations of CO_2 are commonly determined. The upper level of CO_2 concentration for permanent occupancy should not exceed 1000 ppm. Typically, 1000 ppm is used to represent adequate ventilation

(8–10 L/s/person) [37]. Current school ventilation guidance reflects the need to balance the requirement for fresh air with the need to manage energy use by recommending natural ventilation strategies. The carbon dioxide levels in schools are specified in accordance with the guidelines on ventilation, thermal comfort and indoor air quality in schools as follows [39]:

Typical classroom with 30 students and 2 staff occupancy:

- For an outdoor air ventilation rate of 8 to 9 L/s/person, the CO_2 level corresponds to around 1000 ppm under steady state conditions (depending on the ventilation system);
- An outdoor air supply rate of 5 L/s/person corresponds to around 1500 ppm under steady state conditions.

In general, in teaching and learning spaces where natural ventilation is used or when hybrid systems are in operation, the accepted recommendation is the following: sufficient outdoor air change should be provided to achieve a daily average concentration of CO_2 of less than 1500 ppm during the occupied period.

Monitoring of the CO_2 concentration in the classroom's indoor air was performed using the measurement set TESTO 535, as seen in Figure 4. The measurement gauge consists of two apparatuses with probes for indoor and outdoor monitoring (calibration 2017). Outdoor temperature and relative humidity were controlled using the gauge TESTO 645 (calibration 2017).

External probe on window parapet	Internal probe in unoccupied room	Internal probe in occupied room

Figure 4. Set for measurement of CO_2 concentration in the classroom.

The measurement was completed for the classroom's former and newly renovated states in comparable ways. Teachers and pupils were informed about the measurements. The monitoring was first carried out in unoccupied classrooms (before educational time) and then with occupancy during teaching hours. Measurements were also provided for a corridor next to the classroom and for outdoor air outside the school. Measurements were always carried out on two days a week, usually on Thursdays and Fridays. On Thursdays, the classroom windows were randomly opened depending on the teacher's decision and subjective feeling, but on Fridays, the window opening was operated by the measurement staff. Measurements were carried out in 5–10-min intervals between 7:30 and 13:20. The internal measurement sensor was placed 1.35 m above floor level in the middle of the room.

2.3. Microbial Testing

The objective of this study was to investigate the existence of airborne fungi and bacteria in the classroom environment. A quantitative evaluation of the viable bioaerosols' sampling was performed. The quantity of bioaerosols in indoor air is dynamic. The dynamic variation of fungi and bacteria in indoor air is influenced by many other factors, such as the room's volume of air change per hour, internal surfaces, furniture and equipment as well as the occupants' behaviour, the room's hygro-thermal conditions, etc. The importance of microbial testing is specified in the document from the World Health Organisation [43].

The microbial testing carried out in the school classroom was conducted according to the standard procedure [57]. Internal surfaces of the classroom were selected for testing. Wooden desks, PVC floor finishing and wall plaster surfaces were tested using a 3 M Sponge-Stick. The tested area of individual surfaces was about 0.45 m × 0.6 m. The sponge contaminated by the surface was placed into a sack with a 50-millilitre solution of NaCl and distilled water (concentration: 8.5 g of NaCl in 1000 mL of water). Then, the sample was placed into the homogeniser Stomacher and finally placed into Petri dishes. The bacteriological substrate plate count agar PCA (Biocar Diagnostics) was used for microbiological cultivation for 72 h at a temperature of 30 °C. The final microbial analysis was determined using an extract of glucose and chloramphenicol for cultivation for 72 to 120 h at 25 °C.

A microbial report was completed for the analysis of eight samples' Colony-Forming Units (CFU) [43,58]. Report EUR 14988 [58], which is concerned with the strategy and methodology for categorising biological particles in the indoor air of private houses, non-industrial workplaces and public buildings (excluding hospitals), is based on analyses of comprehensive microbial testing in buildings within the European Union. In accordance with this report, the criterion for occupied rooms of public buildings is summarised in Table 1 into categories ranging from a very low to a very high concentration of a mixed population of bacteria and fungi in indoor air [58].

Table 1. Criterion of the concentration of mixed population of bacteria and fungi in the air of occupied rooms [58].

Concentration		Bacteria (CFU/m^3)	Fungi (CFU/m^3)
Category	Very low	<50	<25
	Low	<100	<100
	Medium	<500	<500
	High	<2000	<2000
	Very high	>2000	>2000

3. Results and Discussion

3.1. Results of Monitoring of CO_2 Concentration

The results of the measurements show information about the classroom's indoor conditions and the CO_2 concentration in the classroom (volume: 131.04 m^3). The classroom has three big windows; each window has area of 1.93 m^2. All windows are oriented to the south.

The concentration of CO_2 emissions depends on the air change in the classroom. Thermal comfort in the room is influenced by the indoor temperature. If the temperature rises, indoor windows are usually opened. Opening windows will help to reduce the indoor temperature and increase the exchange of fresh air in the room. This effect is obvious in the following figure. Figure 5 shows how the natural ventilation due to the window opening could influence the indoor temperature and air CO_2 concentration (measured on 25 May 2017 between 7:00 and 13:00). The interior temperature rose because of the heating, room occupancy and solar gains through the windows. In total, 26 students and two teachers occupied the classroom. They influenced the rise in the CO_2 concentration. Due to the higher indoor temperature, one window ventilation wing was opened for about 30 min. The effect of this is shown in the graph by the decline in the indoor temperature and the reduction in CO_2 emissions. Following this, two windows were alternately opened for about 45 min. Finally, all windows were closed, the indoor temperature reached 25.5 °C and CO_2 emissions were 3835 ppm at the end of morning lessons at 12:00. After that, all three windows were opened, which affected the rapid reduction in CO_2 emissions and indoor temperature.

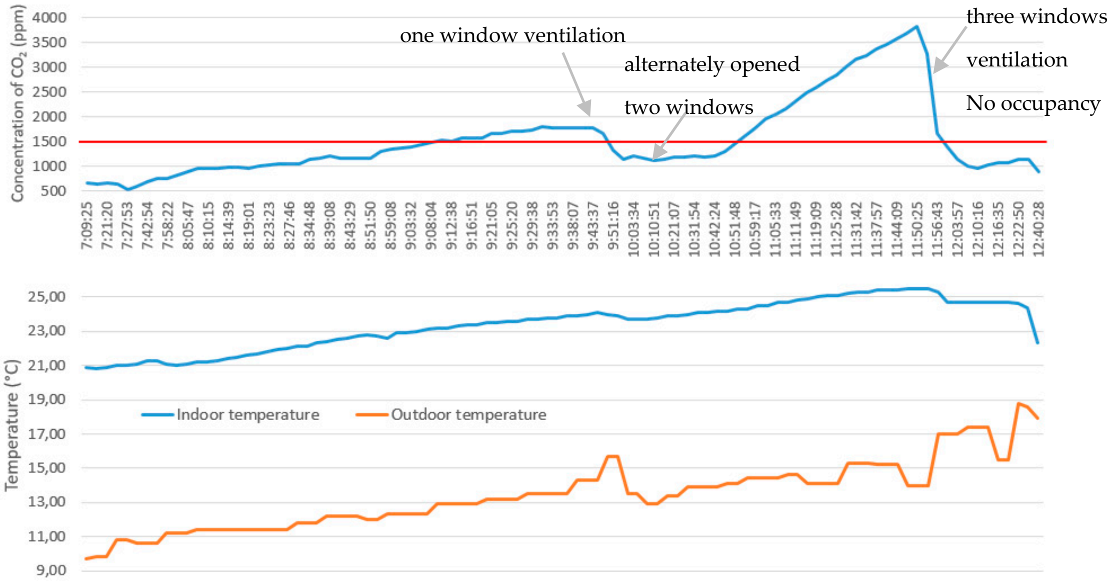


Figure 5. Dependence of CO_2 emissions on the classroom's ventilation (window opening) and indoor and outdoor temperatures.

Characteristic examples of daily profiles of CO_2 concentration and indoor/outdoor temperatures are shown for the following conditions:

- The former classroom, occupancy of 26 students and 2 teachers, air volume per person of 4.68 m^3, natural ventilation, window opening depending on the teacher's decision and clear sky conditions (Figure 6) (2 March, 7:00–13:20);
- The former classroom, occupancy of 26 students and 2 teachers, air volume per person of 4.68 m^3, natural ventilation, controlled window openings and clear sky conditions (Figure 7) (3 March, 7:20–12:30);
- The renovated classroom, occupancy of 21 students and 2 teachers, air volume per person of 5.7 m^3, natural ventilation and window opening depending on the teacher's decision (Figure 8) (30 November, 7:35–12:50);
- The renovated classroom, occupancy of 21 students and 2 teachers, air volume per person of 5.7 m^3, natural ventilation and controlled window openings (Figure 9)_ (1 December, 7:30–12:35).

The CO_2 concentration was influenced by the room's occupancy and ventilation. The windows were opened to allow a fresh air flow into the room and the classroom door was also frequently opened into the school's central corridor. The ventilation schedule was fully subject to the teacher's decision. It means that the CO_2 concentration varied depending on these unexpected situations. An important finding is that the new building state shows a higher concentration of CO_2 emissions. In practice, this means that more intensive ventilation of the classroom is required.

The analysis of data from the measurements in the former and renovated classroom states can be summarised as follows:

- Firstly, the classroom ventilation was based on the thermal comfort of the teacher. It was found that the teacher controlled the air change in the classroom by opening the window. Seemingly, the higher concentration of CO_2 resulted in the low attention of students. However, the main problem in the classroom was overheating because of the big solar gain through the large south-oriented windows. The heating system was not regulated, which resulted in thermal discomfort in the classroom.

- Secondly, a higher concentration of CO_2 was found in the renovated classroom. The heating system was regulated, so interior overheating was eliminated. The windows were opened occasionally.

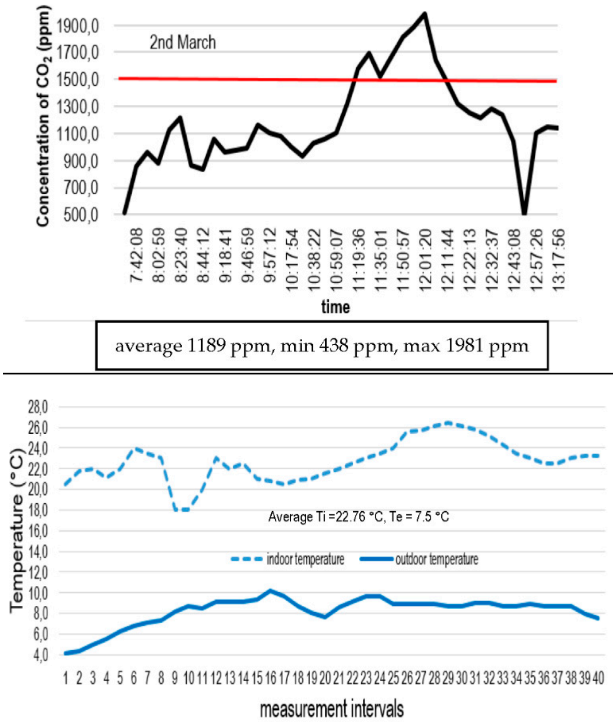


Figure 6. Daily profiles of CO_2 concentration and indoor/outdoor temperatures (2nd March).

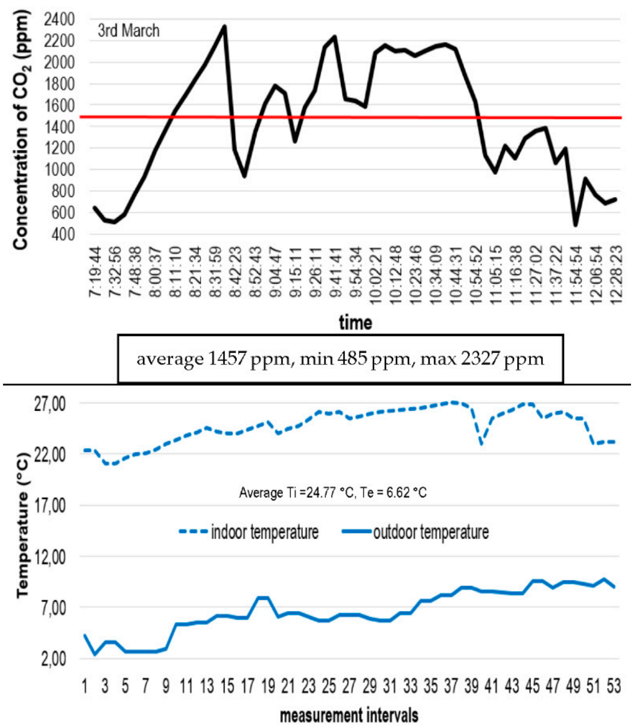


Figure 7. Daily profiles of CO_2 concentration and indoor/outdoor temperatures (3rd March).

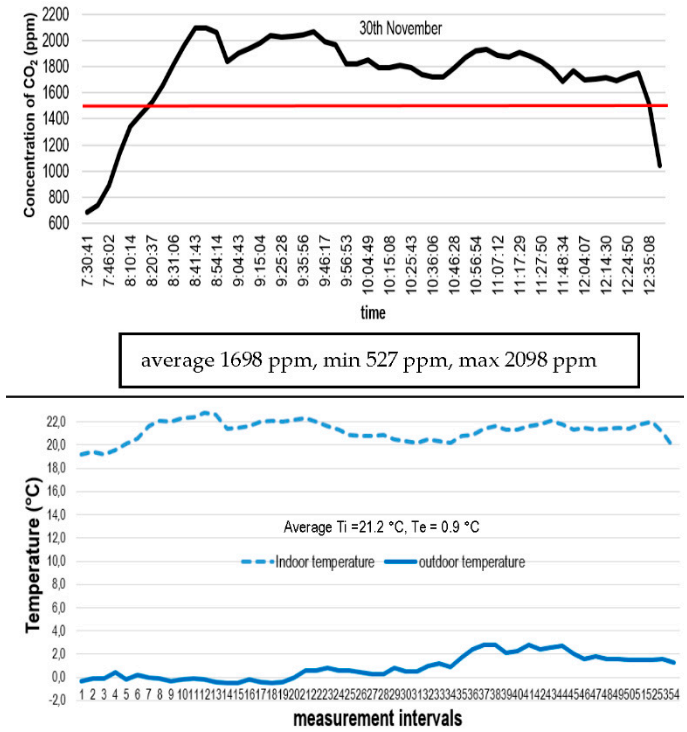


Figure 8. Daily profiles of CO_2 concentration and indoor/outdoor temperatures (30th November).

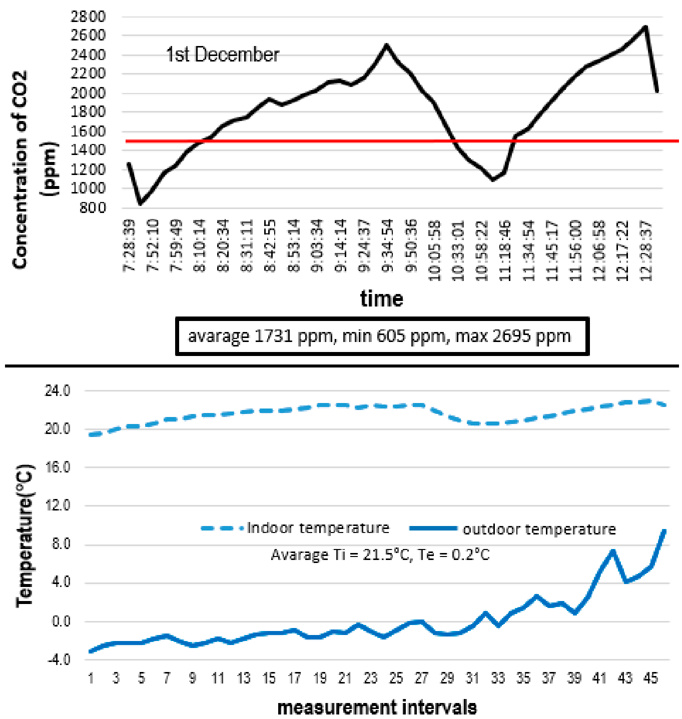


Figure 9. Daily profiles of CO_2 concentration and indoor/outdoor temperatures (1st December).

The measured data of the CO_2 concentration were summarised into the histogram shown in Figure 10. The dominant occurrence of CO_2 emissions in the renovated classroom is obvious. Formerly, the corridor measurements showed a maximum of 1500 ppm, but the renovated corridor CO_2 concentration was increased to over the limit of 1500 ppm (always monitored after the education time). Carbon dioxide was also monitored in the outdoor air. The exterior CO_2 measurements gave a maximum value of 645 ppm.

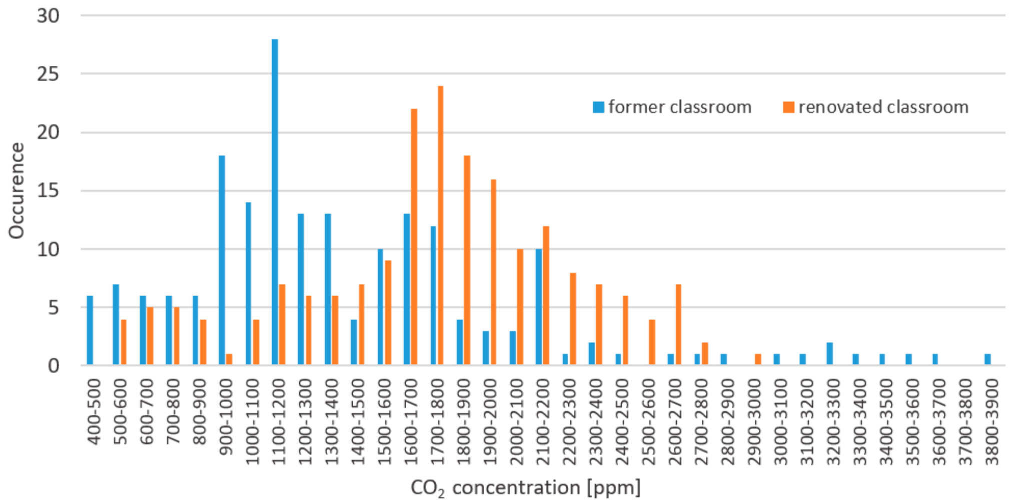


Figure 10. Histogram of mean values of measured CO_2 concentration.

3.2. *Results of Microbial Testing*

Microbial samples were selected in places of potential pollution and mould growth. Microorganisms such as bacteria, moulds and yeasts were identified on the samples. The analysis of the microbiological testing showed that all tested surfaces were mainly affected by fungi, as shown in Table 2 and Figure 11. It is obvious that yeasts were found only on certain surfaces, but all samples were affected by mould. The worst result came from sample 5, which was taken from the PVC floor finishing below the blackboard. Nevertheless, it can be summarised that the microorganisms were not detected in excess. The detection of microorganisms was performed directly after the pupils' occupancy in the afternoon. The classrooms were cleaned early every morning and the desks were washed using disinfectant detergents. Sufficient natural ventilation and the access of solar radiation in the classroom also play positive roles in the classroom's indoor comfort.

Table 2. Result of the microbiological testing in the classroom.

Sample	Surface, Position in the Room	Sample Surface Area	Number of Microorganisms in Colony-Forming Units (CFU) in 50 mL		
			Total Number of Microorganisms	Micromicets	
				Yeast Cells	Fungi
1	Wooden desk, middle of the room	0.6 m × 0.45 m	95,033	Not detected	926
2	Wooden desk, near the central window	0.6 m × 0.45 m	112,626	Not detected	1111
3	Wooden desk, near the opposite wall	0.6 m × 0.45 m	411,544	9511	185
4	Wooden desk, near the front window	0.6 m × 0.45 m	67,656	185	93
5	PVC floor finishing, under the blackboard	0.15 m × 0.60 m	344,444	3033	12,889
6	PVC floor finishing, under the white board	0.15 m × 0.60 m	57,033	Not detected	1111
7	Plaster, wall with the boards	0.20 m × 0.30 m	4717	Not detected	417
8	Plaster, wall opposite windows	0.20 m × 0.30 m	6117	417	417

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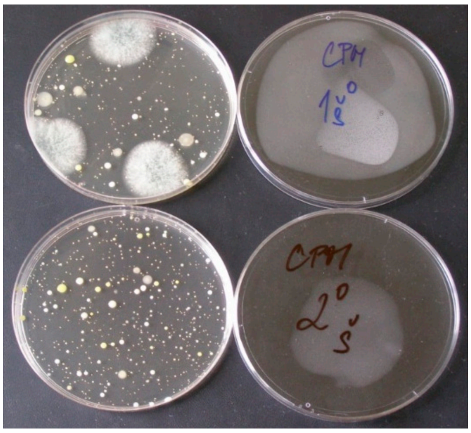
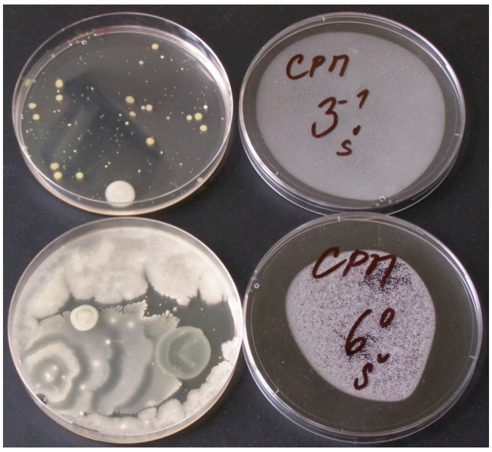
<tr><td></td><td></td></tr>
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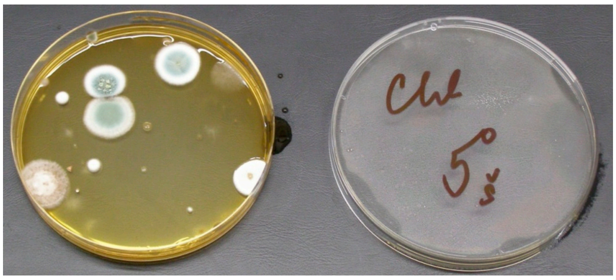
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Penicillium fungi detection</td></tr>
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Figure 11. Photographs from the microbiological testing.

4. Conclusions

A comparative study of the former and renovated states of a school classroom's indoor climate was presented. The study was focused on indoor air quality. The evaluation was based on carbon dioxide concentration monitoring and microbial testing. Measurements of the CO_2 concentration and indoor and outdoor temperatures were carried out for a one-year period during the school building's renovation.

The monitored data show that the indoor air quality in the school classroom is influenced by many factors, especially occupancy and room ventilation. Frequent opening of windows during the classroom occupancy could reduce the carbon dioxide concentration significantly because of the fresh air exchange. Nevertheless, the CO_2 concentration was increased in the renovated school compared to the former classroom, which had a negative influence on indoor climate comfort and study performance.

It was proven that the higher CO_2 concentration was especially due to the installation of new windows. The sealed windows' air exchange appears to be considerably low, which is also in agreement with previous evaluations [59]. This limited window infiltration influences the room's air change. The lower the air change is, the higher the CO_2 concentration is in the occupied room. If not controlled, the indoor air quality decreases in rooms with perfectly airtight windows.

On the other hand, the new thermally insulated and sealed windows reduce the heat losses of the building, which results in the regulation of heating costs. A solution to the indoor climate problem is sufficient ventilation. It was recommended that a roof ventilation unit with a heat recovery system and sensors for CO_2 concentration should be installed.

However, the school classrooms have smaller clearance heights. The installation of suspended ceilings for ventilation pipes would not be a convenient solution. Moreover, the investment price of the central recovery system would be too expensive for the school budget. An instalment of local heat recovery units appears to be an appropriate solution. The units could be installed directly into classrooms and connected to air inlets and outlets.

The results from the microbial testing showed a convenient indoor climate in the newly renovated school. Nevertheless, the testing in the former classroom showed a certain amount of fungal growth. However, the fungal growth was within the tolerable limits according to the current recommendations of the EUR 14988 report [58].

In summary, the air quality of an indoor environment is affected by the CO_2 concentration and the presence of microorganisms. This is influenced by the building's construction and interior furniture, as well as the classroom's occupancy, ventilation schedule and cleanliness. Sufficient natural ventilation and the access of solar radiation in classrooms play key roles in the classroom's indoor comfort. Classroom insulation is needed for a healthy indoor climate, but excessive solar gains can cause thermal as well as visual discomfort. An optimised shading strategy with the application of automatically operated shading systems represent convenient solutions for school classroom windows.

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