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MEASUREMENTS AND ANALYSIS OF AIR TIGHTNESS AND INDOOR AIR QUALITY IN NON-RESIDENTIAL BUILDINGS

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Abstract: Good indoor air quality is crucial factor for achieving healthy and comfortable indoor climate. This issue is critical for public non-residential buildings such are nurseries, hospitals, and schools to avoid phenomena called sick building syndrome. When improving energy efficiency through maintenance and refurbishment, it is recommended to combine thermal insulation of building envelope with the air-tightening of the envelope. Reason for this is an influence of airtightness on energy efficiency, thermal comfort, indoor air quality and moisture condensation. Research presented in this paper is investigating correlation between building's airtightness and levels of CO_2, relative humidity, and temperature as basic parameters for determining indoor thermal comfort. Presented results were obtained by measuring all above stated parameters in classrooms at schools and faculties. All observed buildings are different regarding their age and building technology. During measurements meteorological parameters where also observed as well as the number of occupants in classrooms and the size of classroom itself.

Keywords: indoor air quality, energy efficiency, building airtightness, maintenance, building technology

1. INTRODUCTION

Good indoor air quality is beneficial for health, comfort and productivity [1]. Air tightness of the building helps to avoid uncontrolled airflows through the building envelope, which can lead to problems related to the hygrothermal performance, health, energy consumption, performance of the ventilation systems, thermal comfort, noise, and fire resistance [2]. Air leakage and indoor air exfiltration may cause moisture accumulation or condensation, leading to the microbial growth on materials, change of the properties of the material or even to structural deterioration [2]. The airtightness of the building envelope may be thought to be of central importance when dealing with the problem addressed here [3]. Tight buildings provide increased comfort levels to the occupants, which in turn can have impacts on energy use and acceptability of the indoor environment [4]. Quantification of envelope airtightness is critical to determining how much energy is being lost through infiltration and how much infiltration is contributing toward ventilation requirements [5]. According to the simulations by Jokisalo and Kurnitski, airtightness has a significant effect on the heat energy consumption, by changing air change rate at 50 Pa, n_{50}, between 1, 3, 5 and 10 h^{-1}, heating energy consumption increased from 4% to 21% [9]. For the last five years there were few extensive researches at Faculty of Civil Engineering Osijek regarding building airtightness and summarized results are following:

- Buildings airtightness values are reliant on opaque and transparent part of the envelope, percentage of transparent parts in the envelope and percentage of envelope exposure [6] i.e. building technology and levels of building maintenance,
- Depending on those parameters building airtightness values can be predicted by using neural network prediction model [6] and
- Developed model is not locally conditioned i.e. it can be used outside local area where it is developed [7].

Considering the above-mentioned research results airtightness values can be obtained by using predictive model and then use to determine and simulate carbon dioxide (CO_2) levels in different types of buildings. Research results presented in this paper are considered as preliminary analysis and investigation of correlation between building's airtightness and levels of CO_2, relative humidity and temperature as basic parameters for determining indoor thermal comfort. For this purpose, measurement results from seven classrooms are analysed and presented in this paper.

Classrooms are chosen for analysis since schools have complex indoor environment which is influenced by many factors such as number of occupants, building design, equipment, cleaning agents, and school activities [8]. Most importantly, children spend up to third of the day in these facilities, and thus it is desirable better to understand the environmental quality in these buildings [8].

2. MEASUREMNTS OF AIRTIGHTNESS AND THE INDOOR AIR QUALITY

Limiting airtightness requirements are often to be found in building regulations. When measuring the airtightness of buildings, a blower door method is used to find the relation between the pressure difference over the building envelope, ΔP [Pa], and the airflow rate through the building envelope, Q [m^3/h] [9]. Each classrooms airtightness was measured by using a Minneapolis Blower Door equipment in accordance with EN ISO 13829 later EN ISO 9972:2015 [10, 11], Figure 1. Measurements were carried out following method A - common building use of EN ISO 13829 while applying a pressure difference of 50 Pa. All experiments' results, measurement values, were acceptable as they fulfil EN ISO 13829 criteria, which requires [12]:

- the wind speed lower than 6 m/s,
- the product of maximum building height (m) and temperature difference between outdoor and indoor dry bulb temperature to be lower than 500 m°K,
- the building's volume lower than 4000 m^3.

Measurements of airtightness were carried out during a time when classrooms were unoccupied. Typical air leakage places in classrooms were similar to following ones that can be found in literature [2]:

- junction of the ceiling/floor with the external wall,
- unction of the separating walls with the external wall and roof,
- penetrations of the electrical and plumbing installations through the air barrier systems,
- penetrations of the chimney and ventilation ducts through the air barrier systems,
- leakage around and through electrical sockets and switches and
- leakage around and through windows and doors, figure 1.

Figure 1 - Measurement of airtightness in classroom with Minneapolis Blower Door equipment and detection of typical air leakage places

Classroom ventilation was already recognised as an important determinant of indoor air quality in the beginning of the 20th century; however, even recent studies showed that classroom ventilation rates do not meet building standards [13]. Two studies performed in The Netherlands in 2007 showed that more than 80% of the schools exceeded CO_2 levels of 1200 parts per million (ppm) during classroom occupation, which in The Netherlands is the advised maximum CO_2 concentration for classrooms [13]. CO_2 levels, according to the ASHRAE guideline, are 1000 ppm which is a level above which human comfort may be affected due to potential odours [8]. In the ventilation standard in Sweden it is recommended that indoor CO_2 levels should be below 1000 ppm and that outdoor airflow should be at least 7 l/s per person and additionally 0.35 l/s and m^2 floor surface (National Swedish Board of Occupational Safety and Health 2000) [14]. In another review, it was concluded that beneficial health effects could be achieved by reducing CO_2 down to 800 ppm [14, 15]. A negative association between building age and the prevalence of symptoms has also been demonstrated [15]. Studies carried out by Awbi et al, showed that CO_2 levels as high as 4000 ppm show effects on the student's ability to properly concentrate [16]. Prior research has found that with higher indoor levels of CO_2, indicating less outdoor air ventilation per person, people tend to be less satisfied with indoor air quality, report more acute health symptoms (e.g., headache, mucosal irritation), work slightly slower, and are more often absent from work or school [17]. In this case study, the air quality of classrooms in elementary school and at faculties was examined. The equipment was placed centrally in the classroom, out of reach of the students and out of direct drafts, Figure 2. Indoor air quality in classrooms was measured by using a Datalogger HD37AB17D which can measure and memorize simultaneously the following parameters: relative humidity, environment temperature, carbon monoxide (CO) and CO_2 levels. Fortunately, and as expected, CO levels in all classrooms were equal to zero. Accuracy of CO_2 measurement is ±3ppm +3% of the measured value in the range from 0 to 5000 ppm. Measurement interval for all parameters was 3 second for period of mostly 45 minutes – one school hour in Croatian schools or as long as school hour lasted. Seven classrooms where measurements were taken are labelled in this paper with letters from A to G. A and B labelled classrooms are those at faculty, C and D labelled classrooms are classrooms in one elementary school and E, F and G labelled classrooms are from second elementary school. All of them are in Osijek, Croatia.

Figure 2 - Measurement of indoor air quality in classroom with Datalogger HD37AB17D

3. IN SITU MEASURMENTS IN CLASSROOMS

As mentioned in previous chapter measurements of airtightness and indoor air quality were carried out by using Minneapolis Blower Door equipment for determining n_{50} values of classrooms and Datalogger HD37AB17D for measuring

CO_2 levels, temperature and relative humidity of classrooms. First stage of case study was measurement of airtightness during unoccupied time of classrooms to avoid user disturbances. Second stage of case study was measurement of indoor air quality during classes with students and teacher presence in classroom. Outside meteorological conditions were observed but did not changed noticeably since measurements lasted only 30 to 45 minutes. They are considered constant during this brief period and they are presented in Table 1. Their influence on results is omitted in this study. Nevertheless, outside meteorological conditions should be taken into account and determine their influence on results if measurements were conducted for longer period of time.

Table 1 - Outside meteorological condition during measurements of indoor air quality

Classroom Label	Date and time	Wind speed [m/s]	Air temperature [°C]	Relative humidity [%]	Pressure [hPa]
A	28.11., noon	2	13	37	1024.6
B	16.4., morning	4	9	73	1018.2
C	10.4., morning	3	10	69	1018.2
D	10.4., morning	3	11	60	1018.2
E	25.4., noon	0.7	21	89	1018
F	25.4., noon	0.7	23	85	1018.1
G	25.4., noon	1	22.4	90	1017.8

Building characteristics, i.e. classrooms characteristic according to their age, building technology (type of walls & type of windows), number of students, room geometry and measured airtightness values (n_{50}, $[h^{-1}]$) are presented in Table 2. If measured n_{50} values are compared to those proscribed Technical Regulation on the Rational Use of Energy and Thermal Insulation in Buildings [18] it is evident that 4 classrooms (A, E, F & G) have n_{50} values higher than maximum value of 3,0 h^{-1} prescribed in [18] for buildings with natural ventilation. One of possible reasons for this difference between n_{50} values could be the fact that other classrooms (B, C & D) have new joinery installed in the last five years. All of them are poorly insulated like E, F and G with hollow façade brick layer or have no insulation at all like A, B, C and D buildings i.e. classrooms.

Table 2 – Building characteristics and values of airtightness measurement in classrooms

Classroom Label	Age	Type of walls	Type of windows	Room height [m]	Students	Volume $[m^3]$	Surface $[m^2]$	Floor area $[m^2]$	n50 $[h^{-1}]$
A	62	Brick walls, no insulation	Wood frame, double glazing	2.53	42	240	192	95	12.4
B	30	RC walls, no insulation	Aluminium frame, double glazing	3.53	26	268	276	76	2.8
C	53	Brick walls, no insulation	PVC frame, double glazing	3.16	19	177	151	56	0.85
D	53	Brick walls, no insulation	PVC frame, double glazing	3.13	19	150	143	48	1.11
E	31	RC walls, partially insulated	Aluminium frame, double glazing	2.89	16	162	202	56	9.34
F	31	RC walls, partially insulated	Aluminium frame, double glazing	2.89	12	162	202	56	6.86
G	31	RC walls, partially insulated	Aluminium frame, double glazing	3	25	168	202	56	10.6

Levels of CO_2 were measured and presented for each classroom in ppm, relative humidity in % and temperature in C°. Factors used for indoor air quality were measured every three second during occupancy of classroom. During this time windows and doors were closed. Number of students and teachers was also observed during this period and this number was constant. All classrooms included in this case study have natural ventilation. To ensure data comparability in the following statistical analysis all data were reduced to the same period of 1980 seconds i.e. 33 minutes. This was the shortest period of all conducted measurements in classrooms. Reason for this is different duration of teaching period in observed classrooms. Basic statistical parameters of measured values with their range and arithmetic mean are presented in Table 3.

Table 3 - Means and ranges (minimum and maximum) of observed variables influencing indoor air quality in classrooms during measurement period

Classroom Label	T [°C]			CO2 [ppm]			rH [%]		
	Mean	Range		Mean	Range		Mean	Range	
A	23	22	24	1765	997	2495	29	24	33
B	24	21	25	1100	577	1525	31	30	35
C	23	22	24	1211	957	1497	36	35	37
D	24	22	25	1528	865	2206	45	40	49
E	28	28	28	1127	796	1456	69	66	71
F	28	28	29	1348	1144	1651	68	67	69
G	29	28	29	1790	1176	2502	73	70	76

Second step was determination of statistical correlations of indoor air quality parameters for each classroom. Results are presented in Table 4, marked correlations are significant at $p < .05000$. In all classrooms strong correlation between indoor air quality parameters, CO_2 levels, relative humidity and temperature, is present. Same goes for correlations between temperature and relative humidity but with exceptions in classrooms B and E. There is no obvious reason for this and it needs further investigation and measurements.

Table 4 - Correlations of indoor air quality parameters for each classroom

Variable	Classroom A			Classroom B			Classroom C			Classroom D		
	T [°C]	CO2 [ppm]	rH [%]	T [°C]	CO2 [ppm]	rH [%]	T [°C]	CO2 [ppm]	rH [%]	T [°C]	CO2 [ppm]	rH [%]
T [°C]	1.0000	0.9836	0.9658	1.0000	0.9107	-0.0001	1.0000	0.9184	0.7566	1.0000	0.9764	0.9865
CO2 [ppm]	0.9836	1.0000	0.9682	0.9107	1.0000	0.3980	0.9184	1.0000	0.9071	0.9764	1.0000	0.9917
rH [%]	0.9658	0.9682	1.0000	-0.0001	0.3980	1.0000	0.7566	0.9071	1.0000	0.9865	0.9917	1.0000

Variable	Classroom E			Classroom F			Classroom G		
	T [°C]	CO2 [ppm]	rH [%]	T [°C]	CO2 [ppm]	rH [%]	T [°C]	CO2 [ppm]	rH [%]
T [°C]	1.0000	0.2276	0.0580	1.0000	0.9893	0.5325	1.0000	0.9893	0.5325
CO2 [ppm]	0.2276	1.0000	0.9707	0.9893	1.0000	0.5945	0.9893	1.0000	0.5945
rH [%]	0.0580	0.9707	1.0000	0.5325	0.5945	1.0000	0.5325	0.5945	1.0000

Finally, statistical correlation between following variables was observed:

- n_{50},
- Number of students in classroom,
- Classroom volume,
- Classroom surface,
- Classroom floor area,
- Temperature change during measurement,
- CO_2 concentration change during measurement,
- rH level change during measurement,
- Room height and
- Building age.

Results of the analysis are presented in Table 5 where marked correlations are significant at $p < .05000$. Some of strong correlations were expected to be find like correlation between:

- Number of students in classroom and classroom floor area (0.8796),
- Number of students in classroom and CO_2 concentration change during measurement (0.7556) and
- Classroom volume and classroom floor area (0.8610).

Table 5 - Correlations of indoor air quality parameters and observed variables

Variable	1	2	3	4	5	6	7	8	9	10
1	1	0.4636	0.0882	0.2135	0.4511	-0.4939	0.3045	0.1884	-0.7639	-0.1033
2	0.4636	1	0.6944	0.1795	0.8796	0.4035	0.7556	0.1901	-0.3592	0.5305
3	0.0882	0.6944	1	0.6973	0.8610	0.7643	0.2782	-0.4270	0.2002	0.0895
4	0.2135	0.1795	0.6973	1	0.4432	0.4176	-0.0668	-0.6177	0.3610	-0.6420
5	0.4511	0.8796	0.8610	0.4432	1	0.4337	0.4118	-0.1508	-0.3215	0.3482
6	-0.4939	0.4035	0.7643	0.4176	0.4337	1	0.2741	-0.3645	0.6370	0.1708
7	0.3045	0.7556	0.2782	-0.0668	0.4118	0.2741	1	0.6319	-0.2078	0.4460
8	0.1884	0.1901	-0.4270	-0.6177	-0.1508	-0.3645	0.6319	1	-0.4402	0.4863
9	-0.7639	-0.3592	0.2002	0.3610	-0.3215	0.6370	-0.2078	-0.4402	1	-0.3960
10	-0.1033	0.5305	0.0895	-0.6420	0.3482	0.1708	0.4460	0.4863	-0.3960	1

But there are also some correlations that were not considered in previous research at Faculty of Civil Engineering Osijek regarding building airtightness and indoor air climate, those are:

- Room height and n_{50} values (-0.7638), Figure 3a and
- Classroom volume and temperature change during measurement (0.7642), Figure 3b.

According to presented results room height and n_{50} values are negatively correlated, n_{50} values are higher for classrooms with lower height values. On the opposite side, classroom volume and temperature change during measurement are positively correlated, temperature change during measurement is more prominent in larger classrooms i.e. bigger volume. The low airtightness values and high temperatures and humidity levels suggest that the thermal comfort of the students is compromised and these factors confirm that CO_2 should be used as the controlling factor for measuring ventilation and air quality within and occupied space as suggested in [16].

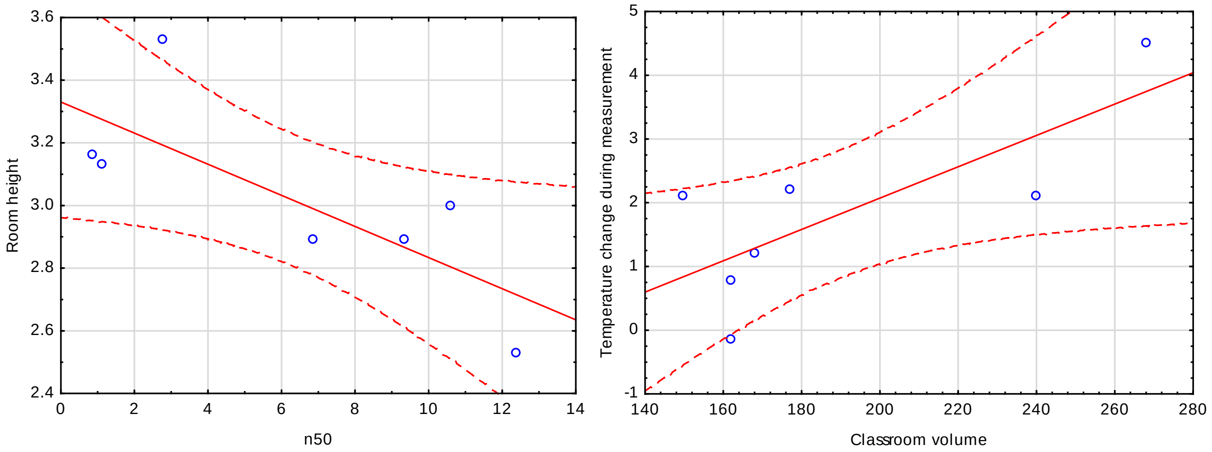

Figure 3 – Graphical presentation of significant correlations between a) room height and n_{50} values and b) classroom volume and temperature change during measurement

Although present at some level, this research did not find strong correlation between n_{50} values and CO_2 concentration change during measurement (0.3044) and n_{50} values and rH level change during measurement (0.1883). Higher correlation levels were found between n_{50} values and classroom floor area (0.4510) and n_{50} values and temperature change during measurement (-0.4939).

Finally, the amount of CO_2 emitted from students was also analysed in this case study. A range for the production of CO_2 for children 4–12 years is 382–546 mg min^{-1} and for adults, a range of 505–709 mg min^{-1} [19]. Some authors account an average CO_2 production by children 6–11 years old of 448 mg min^{-1} and for adults, 763 mg min^{-1} [19]. The variation in the estimated values may result from differences in activity rates, age of occupants, or other possible sources of CO_2 in the classroom [19]. For this case study estimation of an average CO_2 generation rate per child was 546 mg/min^{-1} and 763 mg min^{-1} for college students, this is similar to estimates found in the literature for the age and activity level of elementary students, the classroom occupants [19].

Since estimation of an average CO_2 generation rate per occupant adopted is this study is expressed in mg/min^{-1} additional calculations were needed to express CO_2 emitted from students in ppm. To do so generation rate of CO_2 per occupant was multiplied with number of occupants and measurement duration in minutes. Obtained value was divided with CO_2 density value to get CO_2 volume in cubic meters. CO_2 density value for calculation was 1,842 kg/m^3 for 20°C [20]. Volume of CO_2 emitted from occupant of classroom was divided by classroom volume to get CO_2 concentration in ppm. Correlations between variables when considering an average CO_2 generation rate per occupant are presented in Table 6 where marked correlations are significant at $p < .05000$.

Table 6 - Correlations of CO_2 generation rate per occupant and observed variables

	1	2	3	4	5	6	7	8	9
Variable	n_{50} [1/h]	Number of students	Room height	Building age	Classroom volume	CO_2 concentration at the beginning of measur.	CO_2 concentration at the end of measur.	CO_2 emission from occupants [ppm]	Difference between CO_2 conc. at the end of measur. and emission of CO2 from occup.
1	1	0.4636	-0.7639	-0.1033	0.0882	0.3902	0.4885	0.4973	-0.0880
2	0.4636	1	-0.3592	0.5305	0.6944	-0.1692	0.6288	0.9857	-0.5979
3	-0.7639	-0.3592	1	-0.3960	0.2002	-0.5633	-0.4857	-0.4536	0.0302
4	-0.1033	0.5305	-0.3960	1	0.0895	-0.0136	0.4153	0.5936	-0.3143
5	0.0882	0.6944	0.2002	0.0895	1	-0.5154	-0.0009	0.5768	-0.8098
6	0.3902	-0.1692	-0.5633	-0.0136	-0.5154	1	0.3571	-0.1029	0.5895
7	0.4885	0.6288	-0.4857	0.4153	-0.0009	0.3571	1	0.7209	0.2364
8	0.4973	0.9857	-0.4536	0.5936	0.5768	-0.1029	0.7209	1	-0.5031
9	-0.0880	-0.5979	0.0302	-0.3143	-0.8098	0.5895	0.2364	-0.5031	1

This part of research was directed toward investigation of connections between building age, classroom volume, and room height with CO_2 levels changes. First set of variables (building age, classroom volume, and room height) could be considered as physical characteristics of building. Although sample was rather small, and some correlations were expected to be found, some interesting correlations were found between following variables:

1. Room height and CO_2 concentration at the beginning of measurement (-0.5633),
2. Room height and CO_2 concentration at the end of measurement (-0.4857),
3. Classroom volume and CO_2 concentration at the beginning of measurement (-0.5154),

4. Classroom volume and difference between CO_2 concentration at the end of measurement and emission of CO_2 from occupants (-0.8098) and
5. Building age and CO_2 concentration at the end of measurement (0.4153).

Classrooms with higher ceilings (room height) and consequently bigger volume tend to have better indoor climate conditions considering CO_2 problems (above correlations from 1. to 4.) since they have negative correlations with observed CO_2 parameters. Higher the ceiling and bigger the volume CO_2 concentration at the beginning and at the end of measurement are lower especially when CO_2 generation rate per occupant is considered – correlation 4. is -0.8098 and significant at $p < .05000$, Figure 4. On the other hand, older buildings tend to have problems with CO_2 concentration levels. This was already demonstrated in [15].

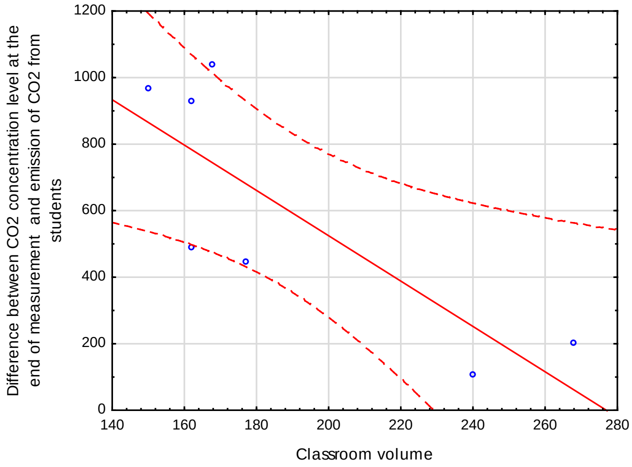

Figure 4 – Graphical presentation of significant correlations between classroom volume and difference between CO_2 concentration at the end of measurement and emission of CO_2 from occupants

4. CONCLUSIONS

Research results presented in this paper are considered as preliminary analysis which tends to define correlation between building's airtightness and indoor air quality. Measurements of airtightness and indoor air quality were carried out in two classrooms at faculty and five classrooms in elementary school. During measurement building characteristics were also described and those are building age, type of walls, type of insulation, type of windows, classroom volume, surface, and room height. Measured n_{50} values were compared to those proscribed in regulations. Four classrooms had n_{50} values higher than maximum value. Reasons for this is the fact that those classrooms are in their original state in terms of wall and joinery quality i.e. they were never refurbished during their life cycle. Presented results are related only for period of time when measurements were undertaken under specified conditions. Research showed strong correlation between indoor air quality parameters, CO_2 levels, relative humidity and temperature. Same was proven for correlations between temperature and relative humidity in most cases. Beside some expected correlations there were also two correlations that were not considered in previous research conducted at Faculty of Civil Engineering Osijek regarding building airtightness and indoor air climate, like correlation between room height and n_{50} values and classroom volume and temperature change during measurement. Room height and n_{50} values are negatively correlated, n_{50} values are higher for classrooms with lower ceilings. Classroom volume and temperature change during measurement are positively correlated, temperature change during measurement is more prominent in larger classrooms i.e. bigger volume. If achieved CO_2 levels at the end of measurement in classrooms are compared to recommended levels of 1000 ppm, CO_2 levels in all classrooms exceeded these values after only 33 minutes of measurement. Overrun of recommended levels ranged from 46% to 150%. Although present at some level, no clear connection between n_{50} values and CO_2 concentration change during measurement and n_{50} values and rH level change during measurement was found. Authors of this paper explain this with partial refurbishment of all observed classrooms. Future research should increase sample and group different types of classrooms according to their building characteristics and type of occupants. In this way influence of airtightness on CO_2 levels changes could be examined more detail. The amount of CO_2 emitted from occupants was also analysed in this research. Classrooms with higher ceilings and consequently bigger volume tend to have better indoor climate conditions considering CO_2 problems. Higher the ceiling and bigger the volume, CO_2 concentration at the beginning and at the end of measurement are lower especially when CO_2 generation rate per occupant is considered. Study also showed that older buildings tend to have problems with CO_2 concentration levels which could lead to sick building syndrome.

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