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Assessing Indoor Air Quality Measurement Correlations and Variations in School Buildings

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Abstract. Schools are suitable type of buildings for Indoor Air Quality (IAQ) measurements. This is justified by the fact that IAQ measurements can ensure a comfortable and healthy environment for educational purposes. The aim of this study is to assess IAQ measurement correlations in 10 school buildings and more detailed correlations and variations in two school buildings. The study also shows challenges related to data transfer in school buildings when sensor or sensors are installed on a different floor than the data transfer unit. In conclusion, both schools' IAQ is good on school days during the research period when the ventilation is switched on. Hence, usually abnormal situations on IAQ occurred in the evenings when the ventilation is switched off.

Keywords: Indoor air quality, school building, monitoring system

1. Introduction

In Western Europe people may be exposed to indoor air even for 20 hours per day. Therefore, Indoor Air Quality (IAQ) is a well researched area due to its health impacts, and large amount of research work has been done related to school buildings IAQ, for example [1], [2]. In school buildings, especially students are at risk of health problems such as allergies and asthma [2]. These health problems have been linked to indoor pollutants commonly found in school buildings. Adequate ventilation is very important, because the comfort and health of school building users are among the many factors that affect attendance and contribute to students learning ability and performance in the classrooms [3]. More energy efficient construction or improvements on energy performance set challenges for good IAQ [4], [5]. Many factors e.g. equipment costs, data transfer set challenges to continuous IAQ measurements and research. Due to these facts, good IAQ is important and these issues cannot be ignored.

This study aims to research indoor air quality measurements correlations in 10 school buildings and in more details correlations and variations in two school buildings located in Kuopio, Finland. In addition, study present challenges related to continuous indoor measurements. Two schools were examined in more detail, because they were constructed in the same year and renovated in successive years, so their comparison was straightforward. In addition, both schools are equipped with similar mechanical exhaust and income ventilation systems with heath recovery, but the average number of students in the classrooms differs. In both schools, ventilation is switched on Mondays to Fridays from 7 am to 4 pm. In addition, schools' ventilation systems are rated according to the S2 classification [12].

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2. Materials and Methods

2.1. Monitoring System and Study Schools

In 2010, the research group of environmental informatics developed the first prototype of a building monitoring and control system [6], [7]. Nowadays, the system is based mostly on commercial products excluding few adapter cards for connecting sensors to ZigBee radio transceiver and user interface. Overall, the system has been installed in 21 residential buildings and in 10 school buildings located in the city of Kuopio, Finland. Utilizing the system, we have collected information on indoor air quality temperature, relative humidity, carbon dioxide (CO_2) and total volatile organic compounds (TVOCs) in these buildings for several years. This study aims to research correlations and variations of the variables in school buildings presented in Table 1, and focusing in more details on schools number 2 and 3. This is done, because their ventilation systems are similar, but the average number of students in the classrooms differs. The average number of students in the classrooms of the school number 2 is 21. Respectively, school number 3 has on average 17 students in the classrooms.

Table 1: Background information on study schools.

School No.	Heated Volume (m^3)	Construction Year	Renovation Year
1	6700	1997	-
2	26130	1968	2006
3	7935	1968	2007
4	19900	1954	2008
5	10350	1953	1992
6	30808	2003	-
7	34235	2011	-
8	21000	1924	1997
9	7000	1935	2004
10	36965	2011	-

The selected school buildings differ from each other in many ways. For example, school number 10 has been constructed recently and it's heated volume is large. In addition, most of the schools are built over 40 years ago and renovated in the last 10 years. This situation makes measurement data very interesting.

2.2. Measurement Arrangements

In the school buildings, IAQ sensors were installed in several classrooms (Table 2). Sensors were installed approximately 1.4-1.8 meters above the floor and far from ventilation ducts and intimacy of windows and doorways. We chose the measurements mentioned above, because they are important indicators for the quality of indoor air. The reliability of the measurements was tested in a few randomly selected classrooms with TSI's IAQ-Calc™ Indoor Air Quality Meter 7525. No significant difference was observed between the TSI and installed sensors.

Typically, the continuous measurements were performed in 5 classrooms in each school excluding school number 6 were measurements were carried out in 7 classrooms. Measurements were taken every 10 seconds. In school number 1, data transfer between sensors and data transfer unit is carried out by wired, which explains the small part of missing values on the measurement period. In all other schools, the data transfer has been carried out wirelessly using ZigBee networks.

2.3. The Challenges Related to Data Transfer and Collection

We have used ZigBee networks for data transfer in sensor networks. Following facts support the choice of technology. ZigBee network uses 16-bit node addressing, which allows theoretically nearly 2^{16} devices on the same network and it allows the use of mesh network topology [8]. ZigBee uses worldwide used 2.4 GHz frequency band in data transmission. Therefore, radios are low priced and easily available.

Table 2: Measurement periods, number of measurements in the schools and missing values of the measurement periods.

School	Measurement Period		Number of Measurements				Missing Values
No.	Start	End	Temp	RH	CO_2	TVOC	(%)
1	11-Oct-2011	11-Jul-2012	5	5	5	1	6
2	10-Nov-2011	12-Jul-2012	5	5	5	1	15
3	10-Nov-2011	12-Jul-2012	5	5	5	2	24
4	10-Nov-2011	12-Jul-2012	5	5	5	1	29
5	10-Nov-2011	4-Jun-2012	5	5	5	2	24
6	10-Nov-2011	12-Jul-2012	7	7	7	2	61
7	11-Nov-2011	22-May-2012	5	5	5	2	43
8	10-Nov-2011	12-Jun-2012	5	5	5	1	67
9	14-Nov-2011	12-Jul-2012	5	5	5	2	57
10	11-Nov-2011	20-Apr-2012	5	5	5	2	68

In the study schools, distances from the data transfer unit (ZigBee coordinator) to sensor nodes (ZigBeerouters) are in the range from 10 to 40 meters. We have noticed that in some cases the radio range is not enough even though the sensor is about 10 meters from the coordinator. Often, these types of data transmission problems occur in cases where sensor or sensors are installed on a different floor than the data transfer unit. This can be explained by the frequency band. Since the ZigBee technology uses the 2.4 GHz frequency band e.g. metal tubes, cables and reinforced concrete in the wall and floors can easily cause reflection even though the distance is very short. In addition, we have noticed that people can cause attenuation of the radio signal. This is reflected in missing values of the measurements during working hours.

Overall, based on our expertise, ZigBee technology is well suitable for indoor data transmission in sensor networks, if the sensors are not far away from each other or the network nodes are placed in such way that the mesh network would work well. Of course, this is not always possible due to furnishing and decoration. If the distances between network nodes are long, it would be better to use different communication technology such as 433 or 868 MHz frequency band radios.

Correlation and Variation Analysis

The data was processed and analysed under a Matlab-software platform (Mathworks, Natick, MA, USA). At the beginning, collected data was pre-processed. This means removing outliers (e.g. measuring errors) and calculating hourly averages of each measured parameter separately from every school. The data is reasonable to analyse on an hourly level, because the changes in IAQ occur slowly.

In this study, we used Pearson's correlation coefficient to measure linear dependences between two measurements [9]-[13]. It ranges from -1 to +1. Correlation ranges and their explanations are presented in Table 3.

Table 3: The interpretation of a correlation coefficient. Presented criteria's are in somehow arbitrary and they should not be observed too strictly [14].

Correlation	Negative	Positive
None	$-0.09 \le R \le 0.0$	$0.0 \le R \le 0.09$
Small	$-0.3 \le R \le -0.1$	$0.1 \le R \le 0.3$
Medium	$-0.5 \le R \le -0.3$	$0.3 \le R \le 0.5$
Strong	$-1.0 \le R \le -0.5$	$0.5 \le R \le 1.0$

Pearson's correlation coefficient between measurements was calculated school by school. We used boxplot figures to analyse diurnal variation of the measurements.

3. Results and Discussion

Statistical information of the measurements is presented school by school in Table 4. There seem to be no major differences between schools, except for one school. Table 4 shows that in school number 1 the mean of relative humidity and its standard deviation differ from other schools. This difference is explained by the swimming pool.

Table 4: Measured parameters and their statistical information.

School	Temp (℃)			RH (%)			CO_2 (ppm)			TVOC (ppm)		
No.	**Mean ± S.D.**	**Min**	**Max**	**Mean ± S.D.**	**Min**	**Max**	**Mean ± S.D.**	**Min**	**Max**	**Mean ± S.D.**	**Min**	**Max**
1	22.0 ± 1.2	18.2	28.1	33 ± 21	4	64	393 ± 61	300	1099	5 ± 5	0	19
2	21.9 ± 1.0	19.1	25.4	20 ± 6	5	53	430 ± 104	307	1943	3 ± 3	0	30
3	21.2 ± 1.1	16.2	25.2	19 ± 6	3	42	384 ± 69	302	1250	4 ± 3	0	24
4	21.6 ± 0.8	19.0	26.3	20 ± 6	0	48	366 ± 90	279	1412	8 ± 6	0	23
5	21.2 ± 1.3	13.0	24.5	17 ± 6	3	36	404 ± 129	298	1901	2 ± 4	0	26
6	21.2 ± 0.9	18.7	24.4	19 ± 5	4	33	418 ± 77	332	1532	1 ± 2	0	8
7	22.6 ± 0.9	20.1	26.2	18 ± 5	4	32	421 ± 97	286	1069	7 ± 6	0	22
8	22.6 ± 1.2	19.6	26.6	18 ± 5	3	32	430 ± 129	321	1497	3 ± 3	0	19
9	21.6 ± 0.9	17.0	24.1	24 ± 6	5	51	388 ± 75	271	865	4 ± 5	0	22
10	22.6 ± 0.6	21.1	25.3	19 ± 3	9	30	433 ± 64	332	1034	3 ± 6	0	21

All the results of Pearson's correlation coefficient analysis are presented in Figure 1. The figure shows that the negative correlation is medium between carbon dioxide (3) and total volatile organic compounds (4) in schools number 3 (R = -0.45) and 7 (R = -0.39). In school number 10, correlation between temperature (1) and total TVOCs (4) differs from other schools significantly. In this case, R reaches the value +0.78. This is due to the fact that this school is constructed in 2011 and materials used on furnishing and decoration are new. New materials evaporate more volatile organic compounds than older ones and the evaporation rate depends on the temperature.

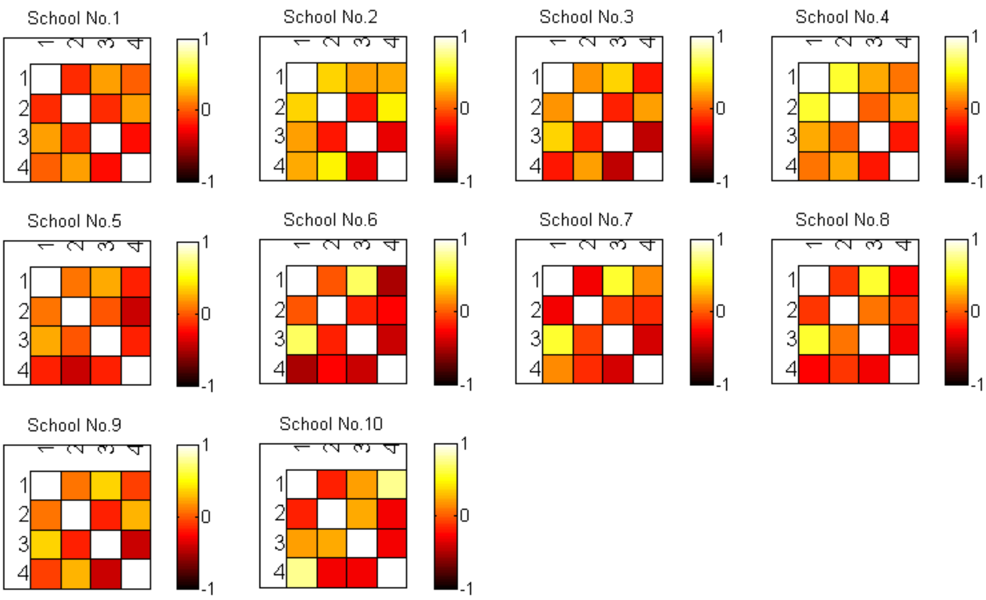

Fig. 1: Correlation map of measurements school by school. Number 1 means temperature, number 2 means relative humidity, number 3 means carbon dioxide and number 4 means total volatile organic compounds.

Next, we evaluate schools number 2 and 3 in more detail using Pearson's correlation coefficient. Calculated correlation matrices are presented in Table 5.

Table 5: Correlation coefficient (R) presented in numbers for all measurements in school number 2 (the left table) and school number 3 (the right table).

School No. 2

	Temp	**RH**	**CO_2**	**TVOC**
Temp	1.00	0.36	0.19	0.24
RH	0.36	1.00	-0.21	0.46
CO_2	0.19	-0.21	1.00	-0.33
TVOC	0.24	0.46	-0.33	1.00

School No. 3

	Temp	**RH**	**CO_2**	**TVOC**
Temp	1.00	0.16	0.35	-0.19
RH	0.16	1.00	-0.18	0.21
CO_2	0.35	-0.18	1.00	-0.45
TVOC	-0.19	0.21	-0.45	1.00

As seen in Table 5, corrections are very similar between the measurements in both schools. Comparing the schools, some small differences can be found:

- Correlations between temperature and TVOCs are opposite. Both correlations are, however, small.
- Positive correlation is medium between temperature and CO_2 in school number 3. Accordingly, positive correlation is small between temperature and CO_2 in school number 2.
- Positive correlation between relative humidity and TVOCs is medium in school number 2. Respectively, correlation between relative humidity and TVOCs is small in school number 3.

Generated box plot diagrams of each measurement, grouped by weekdays, are presented in Figure 2. For temperature, the Finnish guideline value is 21 ℃ and for relative humidity it is 20-60 % during the heating season [10]. In addition, CO_2 concentration should always be under 1500 ppm. Values above 1500 ppm are unacceptable and ventilation should be strengthened. At the moment, the available data do not allow establishing of thresholds for TVOCs [11].

In both schools, statistical distributions of temperature measurements are quite similar. There have been a few abnormal situations on Wednesdays in school number 3. Then the temperature is decreased below 18 ℃. In this case, renovation of the school number 3 does not have a significant effect on temperature variation or statistical distribution. There are no major differences in variations of relative humidity. In school number 2, there have been several abnormal situations from Monday to Friday compared to school number 3.

A significant difference between schools was founded in CO_2 statistical distributions. Variations in CO_2 concentration from Monday to Friday are greater in school number 2 than in school number 3. In addition, CO_2 concentration reaches up the value of 1943 ppm in school number 2. This is a single situation and it occurred in one of the classrooms on Thursday the 26th January 2012 at 5.00 pm to 9.00 pm. During that time, ventilation was switched off. Results indicate that concentration of CO_2 remains more even and CO_2 concentration is lower (nearly always below 900 ppm) in school number 3 due to adequate ventilation.

In school number 2, small variation of TVOCs concentrations was noticed comparing weekdays to weekends. This effect can be caused by human-based emissions (e.g. perspiration, perfume). During the weekends (in both schools), the concentration levels of TVOCs starts to increase due to the ventilation being switched off. In addition, in school number 2 higher concentrations have been observed than in school number 3. After all, concentrations of TVOCs are small and such small concentrations have not impact on health [12].

4. Conclusion

In this study we assess IAQ measurements correlations and variations in school buildings located in Kuopio, Finland. We examined two schools in more detail, because they were constructed in the same year and renovated almost simultaneously, but the number of students differs. In addition, both schools have mechanical exhaust and income ventilation systems with heath recovery. The results show that IAQ variation is smaller in the school number 3. This is perhaps due to the smaller number of students in the classrooms. Overall, the IAQ was good in both schools.

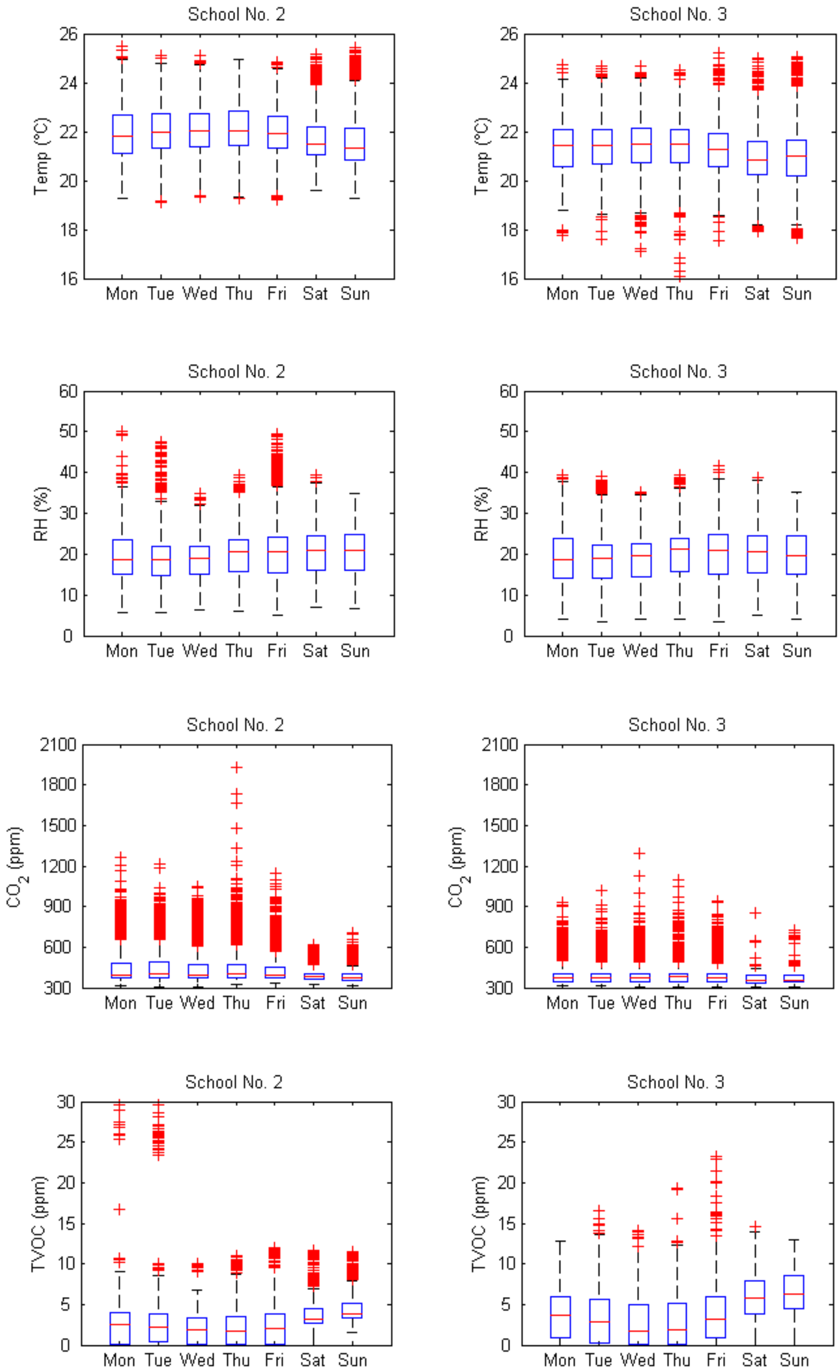

Fig. 2: Statistical distribution of measurements is presented as a box plot diagrams, grouped by weekdays. A box represents the central 50% of the data. Its lower and upper boundary lines are the 25% and 75% quantile of the data. A central line (marked as red) indicates the median of the data. Points beyond the whiskers (remaining data) are displayed using red plus sign (+).

During the study we received valuable information on challenges related to continuous IAQ measurements. After all, building monitoring and control system worked well and we have gathered enough information on our research. As a buildings' owner, the City of Kuopio can utilize these results assessing the quality of indoor air in schools. These experiences are valuable in our upcoming research projects related to utilizing machine learning and computational methods on building automation systems.

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