The Problem of Measurement Accuracy in Sensor Networks for IAQ Monitoring

Andrzej Szczurek, Monika Maciejewska and Tomasz Pietrucha
Laboratory of Sensor Technique and Indoor Air Quality Studies, Wroclaw University of Technology, Wybrzeze Wyspanskiego 27, 57-370, Wroclaw, Poland

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Abstract: These days, the problem of indoor air quality (IAQ) attracts increasing attention. Presently, IAQ is usually characterised on the basis of the following parameters: temperature, relative humidity and carbon dioxide concentration. Because of spatial and temporal variation of these parameters multi-point monitoring systems which operate continuously are preferred. The aim of this work was to show that accuracies of sensors being elements of a network have serious implications for a continuous, fixed-point monitoring of IAQ. The analysis was based on four-point IAQ monitoring study performed in a lecture hall. With reference to the measurement accuracy we computed how likely it was that sensors located in different points recorded the same value of measured quantity and how frequently such situations occurred. It was found that: (1) number of sensors and their displacement affect information provided by the measurement system; (2) these aspects should be considered individually for each parameter describing IAQ ; (3) the sensor device dedicated to each measurement point should be considered individually. By considering these issues in the design process the cost of IAQ monitoring network as well as information redundancy may be reduced.

1 INTRODUCTION

In last decades, indoor air quality (IAQ) has drawn considerable attention in both the public and scientific domains (Fanger, 2006). Due to rising energy costs, buildings are willingly built or renovated to be air tight. In this way, the air exchange between indoor and outdoor environment is seriously reduced. In consequence, the unwanted heat loss is reduced. The negative effect of energy saving is the degradation of air quality in such objects. Bad indoor air quality has a significant impact on human health, safety, productivity and comfort (Sundell, 2004; Sarbu and Pacurar, 2015). This is especially important in developed countries where people spend major fraction of their time indoors.

Recently, much effort has gone into improving indoor air quality (Persily, 2015). In order to perform this task, there is required monitoring of IAQ which provides valuable information to building managers, policy makers, health professionals as well as scientific researchers. In this work, we want to discuss some aspects of the accuracy of measurement devices which should be taken into account in the design of IAQ monitoring system (Hughes and Hase, 2010). Our attention was focused on the influence of sensor accuracy on the location and the composition of sensor unit.

Currently, indoor air quality is rarely monitored (Kim et al., 2015; Varas-Muriel, 2014). Although the need for IAQ monitoring is great, the availability of cost-effective systems is low. Majority of homes and commercial buildings built today are not equipped with IAQ control systems. Regular indoor air monitoring is typically limited to smoke and carbon monoxide (CO) detectors. Some advanced heating, ventilation and air conditioning (HVAC) systems use carbon dioxide (CO_2) sensors to control ventilation (Hesaraki and Holmberg, 2015). HVAC engineers have known for a long time that CO_2 measurements coupled with temperature and humidity readings give an indication of the effectiveness of the HVAC system in the building.

Typical environmental analysis consists of taking single-point measurements of pollutant concentrations. This approach is controversial in the case of IAQ investigation, because parameters describing physical and chemical conditions inside building may vary significantly even within the same room. Especially, indoor pollutants distribution can be spatially non-uniform. Therefore, IAQ monitoring requires a

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cost-effective, widely-accessible, distributed, stationary sensor network, which is capable of measuring selected IAQ parameters at various locations over time, simultaneously (Liu and Zhai, 2009). Basically, this system can be formed by a number of small measuring units which are able to obtain information from their surroundings by means of sensors and transmit it towards a base station using wire or wireless communications. The data from individual monitoring locations are compiled and analyzed. The locations chosen for sensor units depend on the purpose of the monitoring. Using this system, a more detailed representation of IAQ is gained.

Several factors like cost, power consumption, space utilization or measurement characteristics decide about the applicability of sensor networks (Shan et al., 2012; Jelicic et al., 2013). The stationary monitoring network has a serious limitation. It can determine IAQ only at points where sensors are installed. Therefore the appropriate number of fixed monitoring points and reliable sensor localization is a key issue in the design of this system. In practice, the applied sensor units may be too expensive for large-scale and fine grained deployment (Kumar et al., 2011). Thus, existing structures, or even new buildings, with sensor networks is a costly process. The selection of the number of sensors to install and the site for each sensor is one of the most critical aspects to be considered for the overall monitoring system effectiveness. Placing the sensor in the wrong location will defeat the purpose for which it is intended.

IAQ relates to a number of environmental factors, inside a building, which can impinge on the health, comfort or work performance of the buildings occupants. Therefore, real IAQ monitoring systems require multiple types of devices for continuous, in real-time detection and measurements of temperature, humidity, and numerous toxic (hazardous) gases. Currently, different models of sensors are available in the market for monitoring these parameters. IAQ monitoring involves the application of technologies that can provide information at different level of reliability (Peng et al., 2013). Achieving high-quality IAQ evaluation with small number of inexpensive sensors is challenging now.

The aim of this work is to show that the number and location of sensors in IAQ monitoring networks is strongly affected by the accuracies of these measurement devices. Taking this into consideration may allow to reduce data redundancy and build more cost effective and power efficient sensor systems. This is especially important for wireless sensor networks. It should be noted that professional IAQ monitoring systems very often have to face constraints of high power consumption and the excessive cost of applied sensor units.

The rest of the paper is structured as follows. We start from the *Experimental* part which presents the scope of sensors-based IAQ measurement study. The next section, *Methods* contains the description of an approach proposed to study the performance of a sensor set with reference to the accuracies of individual sensors. With this approach we analyzed the outcome of IAQ monitoring study. The obtained results are presented and commented in the *Results and discussion* section. Individual subsections of it are dedicated to temperature, relative humidity and CO_2 measurements. The generalization of our results is proposed in *Conclusions*.

2 EXPERIMENTAL

Indoor air quality monitoirng study was carried out in a university lecture hall, see Fig. 1. The room may be considered as representative for this category of indoor spaces. It has an amphitheatrical layout. Down at the front, a narrow dais is the place for a lecturer. The first row of seats for students starts about some distance from the dais and the last row touches the back wall. Hall dimensions are given in Fig. 2. Desktops and seats form a compact zone, which is a place for 90 listeners (10 rows, 9 seats in each). Lecture hall is fitted with openable windows, which take up one wall. The air is exchanged via natural ventilation.

Figure 1: Lecture hall in which there was conducted IAQ monitoring study.

Measurement session took place in Spring 2015 (April, May, June) and it lasted 8 days. Experiments were performed on Wednesdays in subsequent weeks. We were interested in lecture time i.e. the period from 9:15 to 18:15. Experiments consisted in instrumental

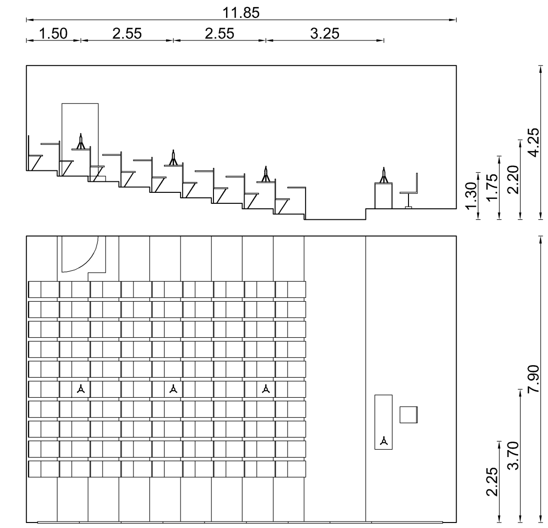

Figure 2: Distribution of measurement points in lecture hall. In each location there were monitored: temperature, relative humidity and CO_2 concentration.

measurements of indoor air parameters and the observation of factors influencing IAQ.

The instrumental part of IAQ study involved the monitoring of three basic indoor air parameters: temperature, relative humidity and carbon dioxide concentration. For this purpose we used sensor devices which measured these three parameters in parallel. Most important technical specifications of sensors are presented in Table 1. They represent a preset standard offered in terms of measurement solutions for the routine determination of indoor air quality. Measurement data was recorded with time resolution of 1 min.

Monitoring was performed at four places within the room. The location of sensor devices is shown in Fig. 2. One of them (no. 1) was placed by the lecturer's seat. Three others were distributed along the hall's central axis in the third (no. 2), sixth (no. 3) and ninth (no. 4) row of seats. Sensor devices were assigned to measurement points. Upon selection of sensors locations we took into account the amphitheatrical layout of the room and students distribution, see Fig. 9. Measuring instruments were placed on desktops i.e. in students' breathing zone. Typically, in the immediate vicinity of sensors the seats were left free in order to eliminate the direct influence of occupants on the readouts.

In addition to sensor measurements there were observed factors which influence IAQ. We considered: number of students present in the room, their spatial distribution, degree of opening for each window, time and duration of windows and door opening, blinds use. The data was collected concerning temporal variation of these factors. The obtained information helped to interpret the results of analysis presented in this work.

3 METHODS

Accuracy of measurement is defined as the closeness of agreement between a measured quantity value and a true quantity value of a measurand (i.e. quantity intended to be measured (JCGM, 200:2008). According to some references (JCGM, 200:2008), the concept "measurement accuracy" is not a quantity and it is not given a numerical value. A measurement is said to be more accurate when it offers a smaller measurement error.

Nevertheless, producers of measurement devices oftentimes provide the numerical information about the accuracy of measurement. It is typically understood as the maximum distance between the true and measured value of a quantity.

We made several assumptions for the purpose of our analysis.

1. The true value x_{true} of the the measurand X belongs to the $2A$-wide interval around the measured value x_m if
$$x_{true} \in \langle x_m - A, x_m + A \rangle \quad (1)$$
where A is the measurement accuracy.

2. Two values x_{true1} and x_{true2} may be considered different if the interval which hosts the true value x_{true1} and the interval which hosts the true value x_{true2} do not have common part. Namely, when
$$\langle x_{m1} - A_1, x_{m1} + A_1 \rangle \cap \langle x_{m2} - A_2, x_{m2} + A_2 \rangle = \varnothing \quad (2)$$
where A_1 and A_2 are the accuracy of measurement 1 and measurement 2 of the same quantity X, respectively.

3. Two values x_{true1} and x_{true2} may be considered equal when the two intervals have common part i.e.
$$\langle x_{m1} - A_1, x_{m1} + A_1 \rangle \cap \langle x_{m2} - A_2, x_{m2} + A_2 \rangle \neq \varnothing. \quad (3)$$

4. Using I_i to denote the interval around the measured value which includes the true value
$$I_i = \langle x_{mi} - A_i, x_{mi} + A_i \rangle \quad (4)$$
one may formulate the generic versions of criteria, given by eq. 2 and eq. 3, which are applicable to $i = 1 \ldots N$ measurement results. Namely, we assume that N true values $x_{true1}, x_{true2}, \ldots, x_{trueN}$ are different, if there is no common part shared by the associated I_i intervals

Table 1: Measuring characteristics of sensors applied for indoor air monitoring.

Measured quantity	Type of sensor	Measuring range	Accuracy	Resolution
carbon dioxide concentration	Non dispersive infrared (NDIR)	0 ... 500 ppm	50 ppm + 3 % m.v.	1 ppm
temperature	Thermistor NTC 10 kΩ	-20 ... 60 °C	0.2 °C or 0.15% m.v.	0.1 °C
relative humidity	Capacitive sensor	5 ... 100%	2 %	0.1 %

$$I_1 \cap I_2 \cap ... I_N = \varnothing. \quad (5)$$

Otherwise, i.e. when N intervals have a part which is common for all of them

$$I_1 \cap I_2 \cap ... I_N \neq \varnothing. \quad (6)$$

then N true values $x_{true1}, x_{true2}, ..., x_{trueN}$ may be recognized as equal.

5. The degree of overlap between intervals I_i may be represented by the width of the interval which is their common part. We used it as the basis for constructing index L

$$L = \frac{|I_1 \cap I_2 \cap ... I_N|}{|2A|} \quad (7)$$

which is the ratio between the width of the actual common part of N intervals and the maximum width of the common part, i.e. $2A$. The index is equal zero in case of lack of overlap. For a complete overlap L equals one.

L may be interpreted as the likelihood that N measurement results refer to the same real value of the measured quantity. In other words, it is a likelihood that a single point measurement would be sufficient to provide the true value of the measurand in the space covered by N measurement points.

We applied the above listed assumptions to analyse the data collected during a four-point IAQ monitoring study which was carried out in a lecture hall. We were interested in the importance of the measurement accuracy in the design of sensor network for IAQ monitoring .

Essentially, we compared measurements performed by $N = 4$ sensors, each located in different measurement point (see Fig. 2). The analysis was performed for pairs of sensors (1-2, 1-3, 1-4, 2-3, 2-4, 3-4), for sensor triplets (1-2-3, 1-2-4, 2-3-4) and for the quartet of sensors (1-2-3-4).

Temperature, relative humidity and carbon dioxide concentration were examined individually. The measurement accuracies used in calculations were following, T: 0.2 °C, RH: 2 % RH and CO_2 concentration: 50 + 3% measured value, as given in Table 1.

The analysis was performed in time steps. A single time step was 1 minute long. Entire monitoring period was divided into such intervals. For a single time step it was determined: 1) whether individual sensors recorded equal values of the measured parameter, 2) the L index.

Based on (1) we computed how frequently a particular set of sensors recorded the same value of the measured quantity during one day. Following (2), all nonzero L values were averaged within the period of one day. The obtained index represented the average degree of overlap between information provided by different measurement points at times when the I intervals overlap existed. The results obtained for individual days were aggregated for the purpose of presentation.

Box and whiskers plot was applied in order to visualize the aggregate results. In the plot, a single box refers to one set of data. The central mark in the box is the median of the data set. The edges of the box are the 25^{th} and 75^{th} percentiles. The whiskers extend to the most extreme data points not considered outliers. Outliers are plotted individually using crosses.

All necessary scripts were written in Matlab.

4 RESULTS AND DISCUSSION

4.1 Temperature

In Fig. 3 we show the results of temperature monitoring in the lecture hall during an exemplary day. More precisely, we plotted the limits of intervals I (see eq. 4) which are expected to host true values of temperature in each measurement point on the subsequent minutes of the monitoring period.

In Fig. 4 we present how frequently sensors located in different measurement points recorded temperature values which could be considered equal. In Table 2 we show the L index which envisages the likelihood that one sensor would be sufficient to provide a true value of temperature, which is representative for all places where the particular set of sensors was distributed.

Based on our results, the existence of common part between I intervals for temperature measured in different locations within lecture hall was basically limited to pairs of sensors. As shown in Fig. 4, an overlap was most frequently observed for measurement points 1-2 (70 % of measurement period), 1-3

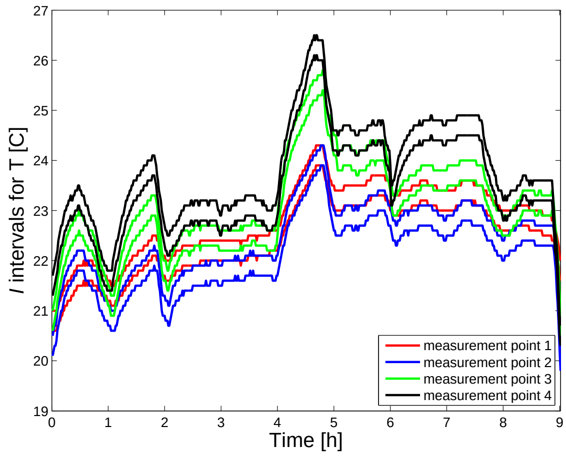

Figure 3: *I* intervals around temperature values recorded by four sensors located in different measurement points. Results come from an exemplary day of the monitoring study.

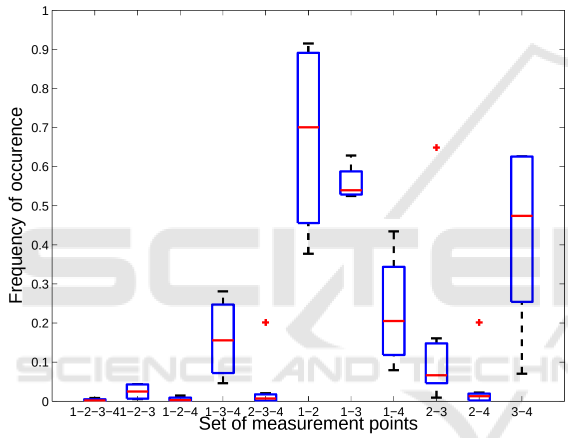

Figure 4: How frequently sensors located in different measurement points recorded temperature values which could be considered equal.

(55 %) and 3-4 (45 %). When the overlap existed, *I* intervals shared about 40 % of their width (see Table 2). Interestingly, we noticed an overlap in pairs 1-2 and 1-3 rather than in pairs 1-2 and 2-3, as would be suggested by the vertical as well as horizontal proximity of sensors (see Fig. 2). This fact may be explained by the exceptional character of location 1. Based on Fig. 3, if one arranged measurement points according to the increasing temperature, the sequence would be as follows: point 2, 1, 3 and 4. Except for point 1, the positions of others in the row could be easily associated with the height of measuring instrument above the lowest floor level. The obtained temperature data reflected the existence of thermal stratification in the room. Sensor 1 recorded greater values than sensor 2 and smaller than sensor 3 because of an additional heat source at the lecturer's seat - a computer system for overhead projection.

Table 2: *L* index for temperature. Average for the cases when there existed a common part of *I* intervals.

Set of measuring points	*I* intervals overlap [%]
1-2-3-4	0.00 ± 0.00
1-2-3	3.26 ± 5.65
1-2-4	5.36 ± 5.26
1-3-4	20.05 ± 10.68
2-3-4	6.56 ± 7.07
1-2	40.15 ± 5.38
1-3	47.35 ± 6.08
1-4	34.86 ± 6.61
2-3	18.14 ± 12.90
2-4	17.21 ± 14.13
3-4	39.99 ± 10.92

In case of three-sensors combinations the same value of temperature was recorded less frequently than 10 % of the overall monitoring period (see Fig. 4). The identity of records form four measurement points was extremely rare, less than 1 % of time.

Our analysis showed that, in an amphitheatrical lecture hall, spatial temperature variation was detectable at a horizontal distance of less than two meters based on measurements performed with the accuracy of 0.2 °C. Therefore, it is reasonable to apply multi-point temperature monitoring indoors using standard instruments. Data redundancy is relatively low. Of course, the ultimate distribution of measurement points would be mainly driven by the goal of maintaining human comfort in an occupied zone.

Temperature sensors are small, cheap and battery powered. Their calibration is rarely required. Sensor devices may operate unattended for weeks, even months. Therefore, numerous measurement points are affordable in case of temperature monitoring indoors. It is important. As we have shown, in view of the available measurement accuracy, there may be required temperature sensors displacement on quite a dense grid in order to properly characterize indoor air.

4.2 Relative Humidity

In Fig. 5 we show the results of relative humidity monitoring in the lecture hall during an exemplary day. More precisely, we plotted the limits of intervals *I* (see eq. 4) which are expected to host true values of RH on the subsequent minutes of the monitoring period in different measurement points.

In Fig. 6 we show how frequently RH sensors placed in different measurement points recorded values which could be considered equal. In Table 3 we present the likelihood that one sensor would be sufficient to provide a true value of humidity, which is representative for all places where particular sensors were located.

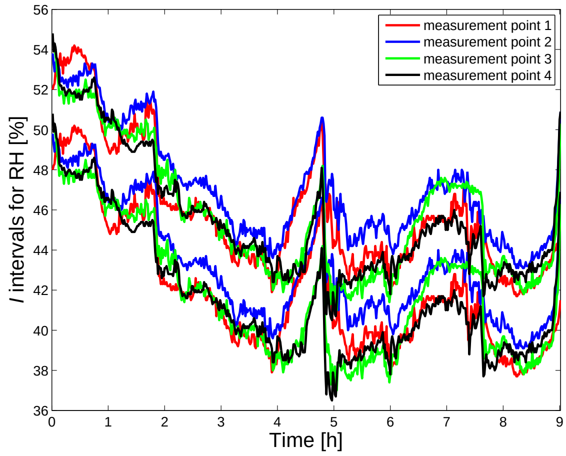

Figure 5: *I* intervals around RH values recorded by four sensors located in different measurement points. Results come from an exemplary day of the monitoring study.

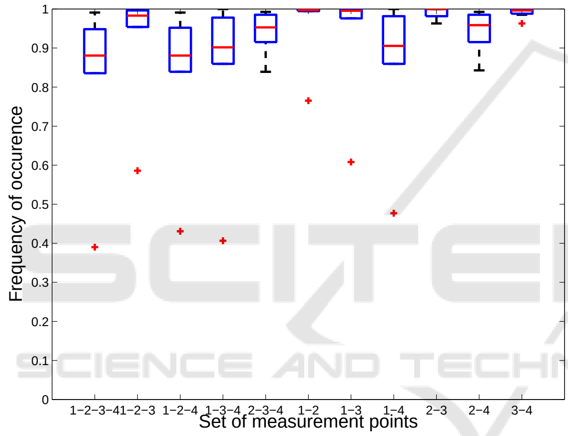

Figure 6: How frequently sensors located in different measurement points recorded relative humidity values which could be considered equal.

Table 3: *L* index for relative humidity. Average for the cases when there existed a common part of *I* intervals.

Set of measuring points	*I* intervals overlap [%]
1-2-3-4	46.99 ± 7.44
1-2-3	50.27 ± 7.99
1-2-4	49.55 ± 7.87
1-3-4	63.07 ± 8.84
2-3-4	56.48 ± 6.29
1-2	65.34 ± 10.67
1-3	66.51 ± 10.61
1-4	64.92 ± 10.15
2-3	66.50 ± 6.12
2-4	63.35 ± 6.94
3-4	79.42 ± 2.52

From our results, the overlap between *I* intervals for RH recorded in different measurement points was very frequent. As shown in Fig. 6, this relation was observed between 80 to 100 % of the overall monitoring period. Computations revealed that the frequency of overlap was nearly the same in groups of two, three as well as all four measurement points. In view of the available RH measurement accuracy, nearly all time of the monitoring study air humidity was the same in each measurement point. Just on one day we observed smaller overlap between RH in measurement point 1 and the remaining locations. Although such occurrences shall not to be ignored, this situation could be considered as episodic.

Based on Fig. 5 also the degree of overlap between *I* intervals around RH values recorded simultaneously in different measurement points was very high. From the numbers given in Table 3 we see that in case of entire sensor network, common part of *I* intervals was as big as 47 %. Of course, for individual pairs of sensors the degree of overlap was still higher and equal 60 to 80 %.

Very high frequency and degree of overlap for *I* intervals in case of RH pointed at the considerable redundancy while using multi-point layout for collecting data about air humidity. Instruments which measure RH with the accuracy of 2 % were not able to detect spatial variation of this parameter in the lecture hall. Actually, when accepting this level of accuracy, the original multi-point monitoring network could be reduced down to one measurement point. In case of taking care for the lecturers comfort individually, two RH sensors would be needed, one located in point 1 and the other located at point 2, 3 or 4.

Similar as in case of temperature measuring units, humidity sensors are small, cheap and durable. From the point of view of cost, installation and maintenance multi-point RH monitoring networks indoors are affordable. However, our findings indicate that they may not be needed. Their creation shall be carefully thought over, with reference to the accuracy of the available measuring devices.

4.3 CO_2 Concentration

In Fig. 7 we show the results of CO_2 concentration monitoring in the lecture hall during an exemplary day. More precisely, we plotted the limits of *I* intervals (see eq. 4) which are expected to host true values of CO_2 concentration in each measurement point on the subsequent minutes of the monitoring period.

In Fig. 8 we show how frequently carbon dioxide sensors located along the main axis in the lecture hall and at the lecturers seat rerecorded concentrations which could be considered equal. In Table 4 we present the probability that one sensor would be sufficient to provide a true value of CO_2 concentration,

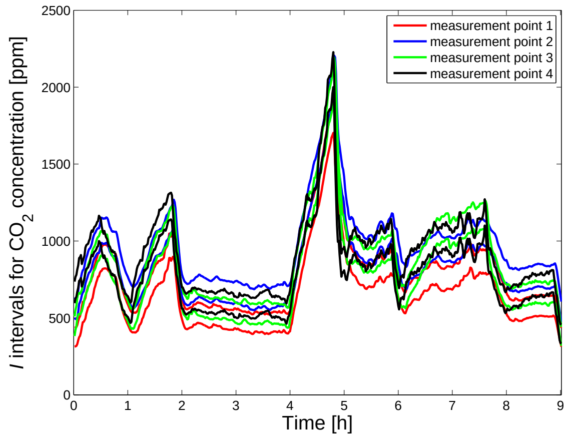

Figure 7: I intervals around CO_2 concentration values recorded by four sensors located in different measurement points. Results come from an exemplary day of the monitoring study.

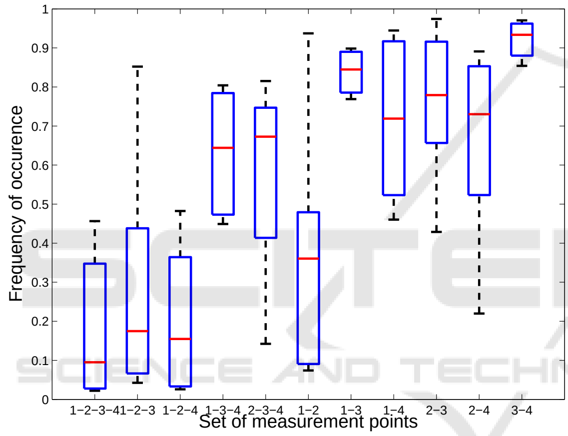

Figure 8: How frequently sensors located in different measurement points recorded CO_2 concentration values which could be considered equal.

which is representative for all places where particular sensors were distributed.

The temporal variation of CO_2 concentration shown in Fig. 6 well reflects room occupancy. Namely, sudden increase of concentration is always associated with the beginning of the lecture, when students enter the room. Sudden decrease appears when students leave the hall for the break.

Based on Fig. 8, most rarely the same CO_2 concentrations were recorded in measurement points 1 and 2. Such situations occurred on average during 40 % of the measurement period. For other pairs of sensors the percentage was much higher from 70 % up to 90 % . The distance between results obtained in point 1 and 2 loaded on the overlap within groups of three or four sensor which included 1-2 pair. In such sensor sets the overlap was infrequent, namely 10 to 20 % of the monitoring period. In case the set

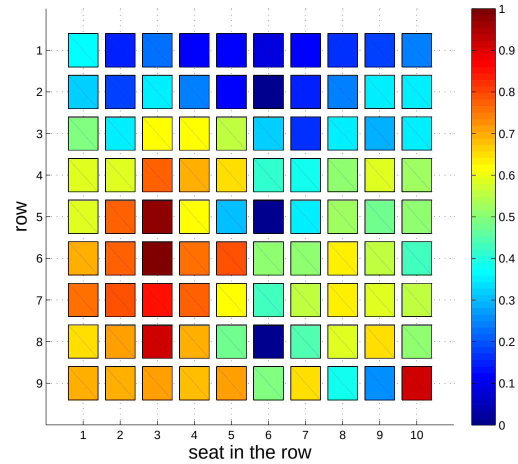

Figure 9: Frequency of student seats occupation. Darkest blue squares indicate location of sensors.

of sensors did not include 1-2 pair the identity of the recorded values was observed during 60 to 70 % of the measurement time. As shown in Table 4, the size of common part of I intervals behaved in the same way as the frequency of overlap occurrence. Namely, the expected regularity was biased due to the dissimilarity of data collected in points 1 and 2. For a particular combination of measurement points the of L index for CO_2 was higher than for temperature and lower as compared with RH.

In Fig. 7 we see that CO_2 concentrations recorded in point 2 were high, compared with other locations. This regularity was observed during entire IAQ monitoring study. High concentrations of CO_2 in point 2 could be attributed to the accumulation of this species in low-lying parts of the room. The molecular mass of this substance is larger compared with air. As shown in Fig. 9 Students, who are the major source of CO_2 in this room rarely took seats in the first rows, i.e. in the vicinity of sensor 2. As a rule, last rows were the

Table 4: L index for CO_2 concentration. Average for the cases when there existed a common part of I intervals.

Set of measuring points	Common part [%]
1-2-3-4	18.29 ± 11.45
1-2-3	25.13 ± 12.40
1-2-4	18.25 ± 10.36
1-3-4	44.74 ± 8.46
2-3-4	33.48 ± 7.13
1-2	27.75 ± 13.97
1-3	53.61 ± 8.82
1-4	52.75 ± 9.21
2-3	49.41 ± 11.43
2-4	42.88 ± 11.73
3-4	62.77 ± 7.60

heavily occupied part of the room. For this reason concentrations recorded in points 3 and 4 were most frequently high and could be considered identical (90 %, see Fig. 8). Interestingly, results of lecturers seat monitoring (point 1) frequently overlapped with the concentrations up in the audience (80 % of time, see Fig. 8).

From the above presented analysis we see that the distinctive, important locations for CO_2 monitoring were associated with low-lying parts of the room and heavily occupied sections. There, the species should be controlled. In case of the examined lecture hall, the sufficient information about CO_2 concentration could be acquired using two measurement points namely, point 2 (low-lying part of the room) and point 4 or 3 (heavily occupied zone). Setting more points resulted in redundant information if measurements were performed with the accuracy of 50 ppm + 3 % m.v.

CO_2 sensors are several times more expensive compared with temperature and RH sensors. They require relatively frequent calibration and consume much more energy. If measurements session lasts longer than several days CO_2 measurement devices shall be connected to power supply in order to assure the continuity of readouts. These constraints have to be taken under consideration while setting CO_2 monitoring network. However, based on our analysis small number of CO_2 measurement points may not impair the quality of information about this species. Contrarily, in view of the offered measurement accuracies such sensor nets may be recommended.

5 CONCLUSIONS

Temporal and spatial variability of IAQ causes that it should be determined by multi-point sensor networks which operate continuously.

Many factors affect the quality of information which is acquired in this way. These are, for example the number of sensors, their localization and the characteristics of measurement devices. In practical applications, the optimization of these factors is very important.

In our opinion it is necessary that the accuracy of measurement devices is taken under consideration in the selection of the number and distribution of sensors.

This parameter may be different in various commercially offered temperature, RH and CO_2 sensors. In this work, we have shown that also the relation of accuracy to spatial and temporal variation may be different among quantities measured in indoor air. For this reason, the sensor net should be designed individually for each parameter.

Based on our study, the measurement accuracy allows to apply small number of sensors in RH and CO_2 measurements, while in case of temperature, their number should be grater. However, in our opinion the determination of the number of sensors and their distribution shall be based on the screening study and the analysis, which needs to be performed individually for a particular object of interest. This opinion finds the justification in a strong influence of HVAC system, occupancy and building characteristics on the parameters describing IAQ.

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