

Article

Indoor Air CO₂ Sensors and Possible Uncertainties of Measurements: A Review and an Example of Practical Measurements

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Abstract: Since the COVID-19 outbreak, special attention has been paid to proper ventilation and building management systems. The indoor air CO₂ concentration level is still used as an effective indicator to evaluate indoor air quality. Many different sensors have appeared on the market in the last two years. However, calibration procedures and guidance on proper installation have not been well described by manufacturers. The research method is based on a review of technical parameters. The practical measurements of CO₂ concentration were taken using different sensors. For these purposes three different premises were selected. It was found that CO₂ measurement failure happened in residential buildings without mechanical ventilation. Meanwhile, in well ventilated buildings all sensors have shown similar results and the difference between sensors located in different zones was minimal.



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1. Introduction

Indoor air quality monitoring has become a very important subject since the mid 1970s of the last century, when the first energy crisis hit Europe and EU directives aimed at improving energy efficiency in the building sector [1]. The energy to keep an optimal ventilation and thermal comfort plays a crucial role in overall energy balance [2–4]. Since then, particular attention has been paid to building energy consumption and subsequently to buildings airtightness. Ventilation plays an important role in all climatic zones [5–7] and must be properly operated to ensure buildings' energy efficiency as well as optimal indoor air quality and thermal comfort. Several studies have reported a significant decrease in indoor air quality over the past decades. On the contrary, the severe acute respiratory syndrome coronavirus-2/coronavirus disease 2019 (COVID-19) pandemic has highlighted the importance of maintaining a sufficient indoor air exchange rate [8]. The CO₂ is being commonly used as a general parameter, which characterizes the level of indoor pollution [9–11]. Control of ventilation and air condition systems based on CO₂ monitoring have been reported as one of the most energy efficient and economically viable solutions [12,13]. It allows for keeping the balance between energy consumption and indoor air quality [3,14,15]. For example, optimization of ventilation systems in a single family house can ensure a reduction of energy consumption by 38% in Latvian climatic conditions [16]. However, reliability of modern CO₂ sensors is still under investigation. In addition, ASHRAE's Position Document on Indoor Carbon Dioxide [17] concludes that CO₂ concentration does not provide general information on indoor air quality, yet it can be a useful tool in the assessment of indoor air quality if users understand the limitations of the use of this method. An important step to understand CO₂ monitoring and its integration into Building Information Modeling (BIM) is to select proper sensors and position them with respect to the human occupancy zones.

In addition, to decreasing the spread of infections, a solution is needed to measure the density of people per m^2 . It can be accomplished with the help of computer vision [18]. The use of cameras and computer vision will also allow for controlling the number of people in a closed area room, thus obeying pandemic legislation, as well as will training the computer vision to detect whether masks are being worn in the office space. The safety guidelines suggest maintaining distance between people when performing daily duties [19]. The usage of beacons would give a precise understanding of the placement of employees and would provide notification if the distance between them was less than 2 m.

The COVID-19 pandemic caused by the SARS-CoV-2 virus reached Latvia in March 2020, with an average of 7.4 new cases daily and an average 14-day cumulative incidence of 3.1 ± 4.5 until late September 2020 [20]. In the last two years, the outbreak of novel coronavirus SARS-CoV-2 has posed a significant effect on global health having a negative impact also on social and economic fields in different parts of the world, including Latvia [21].

The paper describes the workplace specific COVID-19 risks and identifies required sensing capabilities to assess and to minimize these risks. One of the distinctive features of the paper is combination of various Internet of Things (IoT) sensing. While many of the solutions rely on massive testing, wearable devices, and other intrusive methods or do not provide timely identification of threats and response [22–25], this study proposes to combine various sensing technologies to achieve timely and non-intrusive detection of infection threats and to enact suitable response mechanisms. The paper is structured as follows: Section 2 presents the air quality sensors review, calibration specifics of commercially available sensors, including details of the operation of ventilation systems and sensors placement. Section 3 presents the results of the field tests of three different buildings. Section 4 discusses the results, and Section 5 summarizes the paper results.

The preventive and prescriptive activities are triggered on the basis of monitoring performed using IoT technologies. The IoT technologies considered are air quality monitoring sensors, cameras, and Bluetooth beacons.

This article focuses on the analysis of different CO₂ sensors and its measurements in the room in real occupancy conditions.

2. Materials and Methods

The study concerns identification of required data sets, sensors needed for data gathering and data retrieval methods to obtain comprehensive information about the work environment from the COVID-19 perspective. The present work aims to analyze air quality monitoring sensor models to compare CO₂ measurements taken by different sensors and to address their location and data exchange techniques. The necessary actions will also be identified to improve workplace conditions. These include integration with building management systems to adjust ventilation according to the number of people and risk level, adaptive planning, and reactive notifications to employees.

2.1. Air Quality Sensors

2.1.1. Review of Existing NDIR Sensors

There are four main types of CO₂ sensors:

1. Non-dispersive infrared (NDIR).
2. Electrochemical.
3. Semiconductor.
4. Catalytic combustion.

Semiconductor sensors can be used to measure the concentration of greenhouse gases [26]. Such sensors allow for a wide application for different needs. Some types of electrochemical Li+-garnet-based sensors can reach a one minute response time at low temperatures in the surrounding environment to track 400–4000 ppm levels of CO₂ [27].

Catalytic combustion CO₂ sensors uses the catalyst coating on the surface of a specific type of resistor [28]. The measurements are based on gas catalytically burning on the surface.

The most common principles for CO₂ sensors are infrared gas sensors (NDIR) (Figure 1) and chemical gas sensors. The main benefit of modern NDIR sensors compared to older sensors is a lower energy consumption. According to the existing data, modern sensors consume only 3 mW of power, while typical incandescent IR sensors consume between 50 to 200 mW [29]. CO₂ sensors based on rigid ceramic materials feature the highest energy consumption-up to 200 W [30]. New sensors allow for long term operation using typical AA type batteries. For example, the operation of a Telair 7001 IAQ monitoring sensor (Figure 2) on four AA batteries was approximately 70 h. Some professional sensors have a special calibration probe, while household sensors are calibrated mainly by using general assumption on outdoor air CO₂ concentration.

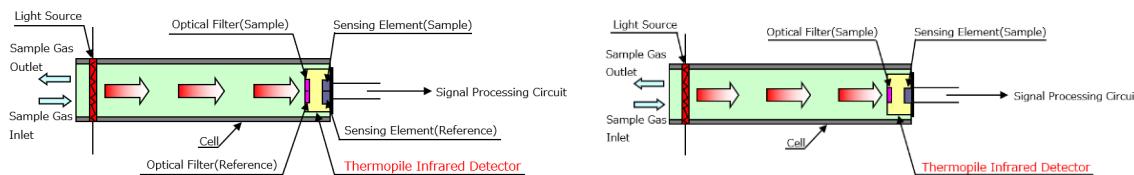


Figure 1. Scheme of NDIR sensors [31].

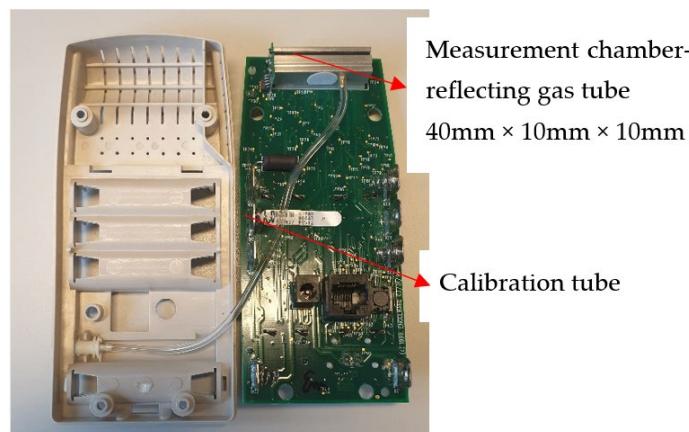


Figure 2. Monitoring sensors architecture (Telair 7001 (old type sensor)).

Dual light sensors are characterized by little changed value even in long-term use and are suitable for the IAQ monitoring and installation in building management systems. Single light wavelength sensors are relatively cheap but can have a large deviation when in long-term use.

Previously, widely used sensors used a reflecting gas tube, which required an extra installation place. Alternative solutions that allow for the reduction of the overall size of sensors propose to use fully integrated on-chip sensors, which use an integrating cylinder as a sensing cavity (see Figure 3).

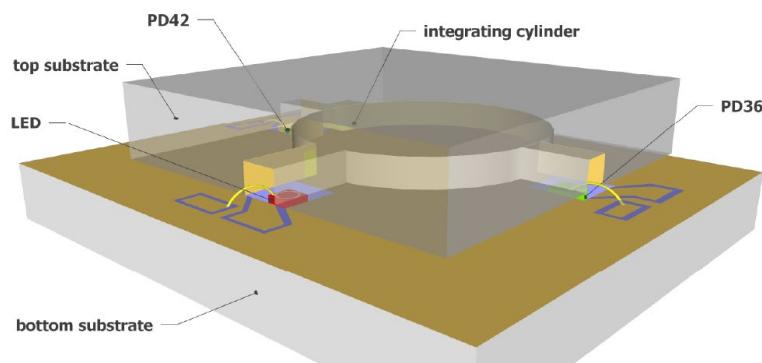


Figure 3. Schematic of the fully integrated on-chip NDIR CO₂ sensor [32].

Before mentioned, CO₂ sensor has a footprint of ~7 mm² with a radius = 2.6 mm. Equivalent optical path length is equal to 3.4 cm.

Tables 1–3 present a brief summary of working parameters of commercially available CO₂ sensors. Two types of sensors were considered for the analysis—“ready to use” and modules. Modules can be integrated in any shell according to the chosen design approach.

Table 1. List of analyzed LAQ sensors available on the market.

| | Model | Type of Sensor |
|-----------------|---------------|--------------------------|
| Ready to use | HOBO MX1102 | NDIR self-calibrating |
| | Extech SD800 | dual wavelength NDIR |
| | Aranet4 HOME | NDIR |
| | Aranet4 PRO | NDIR |
| | Testo 160 IAQ | No data |
| Separate module | MH-Z19B | NDIR infrared gas module |
| | CM1106H-NS | NDIR |
| | MH-Z14B | NDIR infrared gas module |
| | SCD30 | NDIR |

Table 2. Working parameters of analyzed sensors.

| Model | Measurement Parameters | | | | Measurement Range | | | |
|--------------|------------------------|-------------|-------------------|---------------------|-------------------|--------------|-------------------|---------------------|
| | CO ₂ | Temperature | Relative Humidity | Atmosphere Pressure | CO ₂ | Temperature | Relative Humidity | Atmosphere Pressure |
| Ready to use | HOBO MX1102 | + | + | + | - | 0 to 5000 | 0 to 50 °C | 1% to 70% |
| | Extech SD800 | + | + | + | - | 0 to 4000 | 0 to 50 °C | 10 to 90% |
| | Aranet4 HOME | + | + | + | + | 0 to 9999 | 0 to 50 °C | 0 to 85% |
| | Aranet4 PRO | + | + | + | + | 0 to 9999 | 0 to 50 °C | 0 to 85% |
| | Testo 160 IAQ | + | + | + | + | 0 to 5000 | 0 to 50 °C | 0 to 100% |
| Modules | MH-Z19B | + | - | - | - | 0 to ~10,000 | - | - |
| | CM1106H-NS | + | - | - | - | 0 to 2000 | - | - |
| | MH-Z14B | + | - | - | - | 0 to ~10,000 | - | - |
| | SCD30 | + | + | + | - | 0 to 40,000 | −40 °C to 70 °C | 0 to 100% |

Table 3. Measurement precision of analyzed sensors.

| Model | Measurements Precision | | | |
|--------------|------------------------|---|-------------------|----------------------|
| | CO ₂ | Temperature | Relative Humidity | Atmospheric Pressure |
| Ready to use | HOBO MX1102 | ±50 ppm ± 5% | ±0.21 °C | ±2% |
| | Extech SD800 | ±40 ppm (<1000 ppm); ±5% (>1000 ppm) | ±0.8 °C | ±4% |
| | Aranet4 HOME | ±30 ppm ± 3% | ±0.3 °C | ±3% |
| | Aranet4 PRO | ±30 ppm ± 3% | ±0.3 °C | ±3% |
| | Testo 160 IAQ | ±50 ppm + 3% | ±0.5 °C | ±2%; ±3% |
| Modules | MH-Z19B | ±50 ppm + 5% | - | - |
| | CM1106H-NS | ±30 ppm + 3% | - | - |
| | MH-Z14B | ±50 ppm + 5% | - | - |
| | SCD30 | ±30 ppm ± 3% | ±0.4 °C | ±3% |

“Ready to use” sensors means that they are ready to make measurements and record data, and they have the necessary control interface, while modules are used by final product producers and are integrated in the final product.

As can be seen, all commercially available modern sensors use the NDIR technology. However, it should be mentioned that precision of CO₂ measurements of older models were strictly dependent on air temperature [33,34]. Recent study [35] has shown good performance of low-cost sensors. However, the performance of used sensors was not compared to calibrated sensors.

Other studies made a comparison of wireless air quality sensors [36,37]. The results have shown that the analyzed sensors performed satisfactorily in terms of temperature measurement. It was concluded that significant improvements in CO₂ concentration measurement should be done before using them as an HVAC unit management signal. It should be noted that the reviewed study focuses on wireless sensors analysis.

2.1.2. Calibration Specifics of Commercially Available Sensors

Calibration specifics of the previously described air quality sensors were summarized in Table 4 “Ready to use sensors” and in Table 5 “Modules”.

Table 4. Calibration specifics of ready to use sensors.

| Model | Calibration Specifics | | |
|--------------------------|--|--|--|
| | Manual Calibration | Automatic Calibration | Height Compensation |
| HOBO MX1102 | Outdoors, dry outdoor air. The sensor needs to stand in the fresh air for 5 min and then it has to be calibrated by pressing and holding the “Calibrate” button for 5 s and within 5 min the sensor will be recalibrated. Calibration value: 400 ppm. | Sensors can also be calibrated automatically within the first 24 h and every 8 days. Calibration occurs after 3 CO ₂ measurements with the lowest indoor value during the first 24 h or day 8. Using this method, it is necessary to leave the room empty (without occupant presence) so that the CO ₂ level in the room evens out with the outdoor value. | During the first configuration, it is necessary to enter the height value above the sea level (in meters). The deviation from the measurements to each mbar from 1.013 mbar can be 0.135%. |
| Extech SD800 | | No calibration mode. Calibrated by the factory. | |
| Aranet4 HOME/Aranet4 PRO | Outdoors in the fresh air, the sensor must be calibrated by moving the calibration switch from “Manual” to “Auto” and back to “Manual”. During calibration, the sensor should stand at a distance of at least 1 m from people and plants. Calibration progress will occur on the screen of the device. | For calibration, it is necessary to take the device outdoors to fresh air conditions (CO ₂ ≤ 420 ppm.) for 8 h each month. | - |
| Testo 160 IAQ | | No calibration mode. Calibrated by the factory. | |

Table 5. Calibration specifics of modules.

| Model | Calibration Specifics | | |
|---------|---|--|--|
| | Manual Calibration | Automatic Calibration | Through the Command |
| MH-Z19B | Connect sensor contact HD at 0 V for 7 s. Before calibration, the sensor must be held for 20 min in the environment of ~400 ppm CO ₂ . | Calibration is carried out daily, considering the lowest CO ₂ concentration value as 400 ppm. | Through “Serial port” the user can send a command that the value of CO ₂ read is 400 ppm. Before calibration, the sensor must be held for 20 min in the environment of ~400 ppm CO ₂ . |

Table 5. Cont.

| Model | Calibration Specifics | | |
|------------|---|---|--|
| | Manual Calibration | Automatic Calibration | Through the Command |
| CM1106H-NS | In an environment of ~400 ppm. A calibration command must be sent to the CO ₂ level sensor. | Calibrated automatically for the first 24 h and every 7 days. Calibration is carried out after CO ₂ measurements with the lowest indoor value during the first 24 h or on day 7. The method requires leaving the room empty (without occupant presence) so that the CO ₂ level in the room is leveled out with the outdoor concentration. | - |
| MH-Z14B | Connect sensor contact HD at 0 V for 7 s. Before calibration, the sensor must be held for 20 min in the environment of ~400 ppm CO ₂ . | Calibration is carried out daily, considering the lowest value as 400 ppm. | Through “Serial port” the user can send a command that the value of CO ₂ read is 400 ppm. Before calibration, the sensor must be 20 min in the environment at 400 ppm CO ₂ . |
| SCD30 | <i>FRC Field-Calibration Algorithm.</i> Sensor to be placed in a medium with known CO ₂ levels (400–2000 ppm.) or in fresh air (~400 ppm). Before calibration, the sensor must operate for 2 min in normal mode. The calibration can be done through Sensirion SEK EvalKit software. <i>ASC Field-Calibration Algorithm.</i> Calibration is carried out daily, considering the lowest value per day as 400 ppm. | | |

As can be seen, almost all analyzed sensors use the lowest measurement as a reference for the outdoor air CO₂ concentration. Some of them require to be brought outdoors and to be calibrated. In general, such calibration could be accepted. However, such calibration should be done with respect to the surrounding environment. Nearby traffic specifics and wind direction could affect the precision of calibration.

2.2. Building Management System

The proper operation of ventilation systems will ensure optimal air exchange and air distribution with respect to buildings' energy efficiency. Ventilation of office buildings and modern apartments buildings is generally provided by mechanical ventilation. Considering growing energy prices, more detailed attention must be paid to building management systems (BMS). In scope of this task the different control measures have been considered to understand how ventilation systems could be managed to reach the best energy efficiency without compromising indoor air quality.

One of the simplest solutions to optimize air supply is variable air volume (VAV). VAV systems (Figure 4) allow precise control of supply air based on indoor air pollution. These systems increase the ventilation rate mainly according to carbon dioxide (CO₂). However, temperature and humidity sensors could also be used to control air supply.

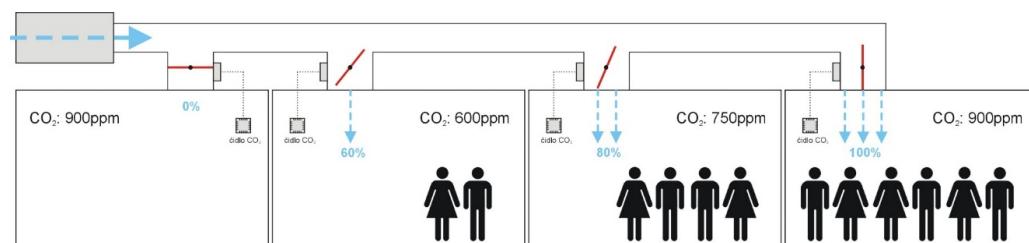


Figure 4. Supply air control solutions using variable air volume (VAV) units (source: <https://www.careforair.eu/wp-content/uploads/2016/02/dcv.jpg> (accessed on 9 September 2022)).

The sensor's correct placement has an important function in obtaining correct measurements (see Section 2.3).

Mui et al. [38] have measured the CO₂ concentration at 12 different locations in an office room with a VAV system. The results showed that 75% of the 12 locations had an acceptable CO₂ concentration, i.e., controlled below the setpoints. This could be explained by non-even human location in the room as well as by non-even air distribution.

Additionally, it should be mentioned that CO₂ based VAV systems do not take into account moisture content and temperature. BMS can allow more precise control of a VAV system by programming an HVAC operation longer than CO₂ sensors show; thus, providing room ventilation before and after occupancy. This will allow moisture and outdoor removal for pre- and post-occupancy periods, especially during the rooms' cleaning procedure.

The control of CO₂ using only VAV systems without extra advanced control can cause difficulties in ensuring precise control of CO₂ and especially maintaining an optimal balance between all major IAQ parameters [39]. According to this study, a user-friendly BMS, which ensures long-term monitoring, can be used for fine ventilation, tuning of air conditioning systems, and prioritization of energy strategies.

2.3. Placement of Sensors

2.3.1. General Description of Air Distribution

Traditional mixing ventilation systems (Figure 5a) have a medium ventilation effectiveness and low energy efficiency. However, such a type of ventilation is still dominant on the market and widely used by engineers. The main benefits of mixing ventilation are well known: standardized design procedure, easy to fit in any room layout, and simple installation. Better efficiency and removal of pollution from a working zone ensures displacement ventilation (Figure 5b).

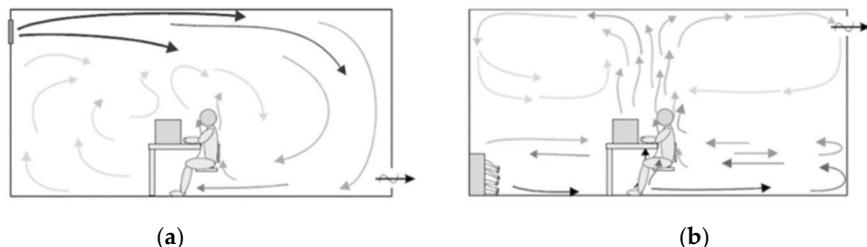


Figure 5. Indoor air distribution approaches in mechanical ventilation systems: (a) Mixing ventilation; (b) Displacement ventilation.

Displacement ventilation allows air removal from a working zone directly to the exhaust without passing through another working zone. However, this requires a more precise design and the planning of ventilation systems and supply vents.

The latest COVID-19 outbreak has highlighted the overall importance of ventilation and air distribution in indoor spaces (Figure 6).

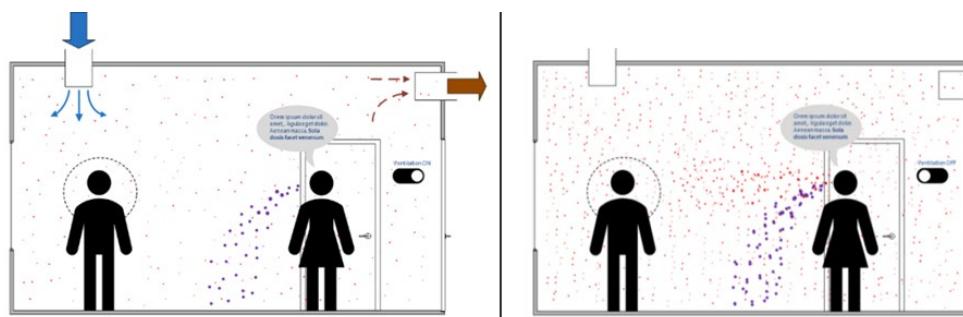


Figure 6. Influence of ventilation on the pollution distribution in a room [40].

As can be seen, placement of supply and exhaust diffusers have a significant role in air distribution and movement of pollutants from person to person. Thus, indoor air quality sensors should be placed cogently in accordance with air distributing patterns.

Relevant technical guidance is available from ASHRAE's Position Document on Infectious Aerosols [41] and relevant online technical resources regarding transmission of SARS-CoV-2 and the operation of HVAC systems during the COVID-19 pandemic [42].

2.3.2. Indoor Air Quality Sensors Placement

Considering that indoor spaces do not have a constant load and that people constantly move, use of only one sensor could provide misleading information on CO₂ concentration in a working zone. The simulation of air distribution in the rooms can be precisely done using computational fluid dynamics (CFD) simulation. Such a type of simulation continuously improves for more than 60 years [43]. Nowadays, CFD is a reliable tool even for estimation of air distribution in very specific cases, such as hospitals, clean rooms etc. [44–46]. Thus, CFD calculation during the design stage can help engineers to choose optimal locations for sensor placement and to provide more precise balancing and tuning for ventilation systems during operation based on the CFD model and real measurements data.

Figure 7 shows the future possible solution for BMS that can include multi sensor placement in all rooms.

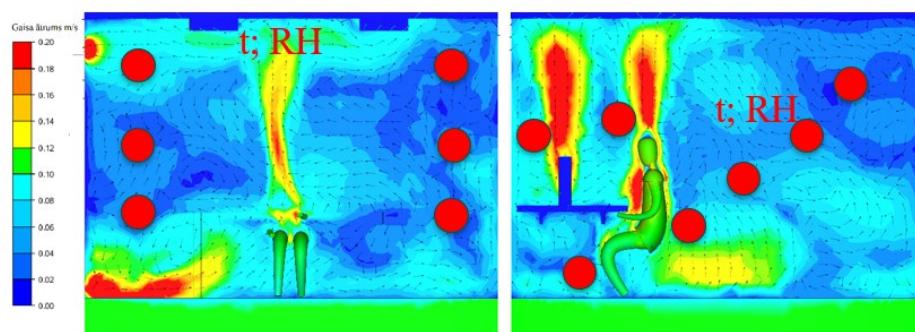


Figure 7. Air distribution pattern in displacement ventilation system and possible sensor placement (adopted from [47]).

The red dots show the possible placement of indoor air quality sensors to ensure precise measurements of air distribution and provide data on CO₂ concentration exactly in working zone. The increasing number of sensors placed in the buildings will require enhanced solution for data collection and analysis. Internet of Things (IoT) should be considered for future building operation [48], especially in large-scale buildings.

3. Results

Placement of IAQ Sensors in Office Building

As a test bed, several locations in Riga (Latvia) were chosen. The focus was paid to three case studies: office building with several rooms (Case 1), separate university staff room (Case 2), and apartment bedroom (Case 3).

Figure 8 presets placement of TESTO 480 measurement equipment, the supply air flow measurement from diffusers was held in several rooms of the corresponding office.

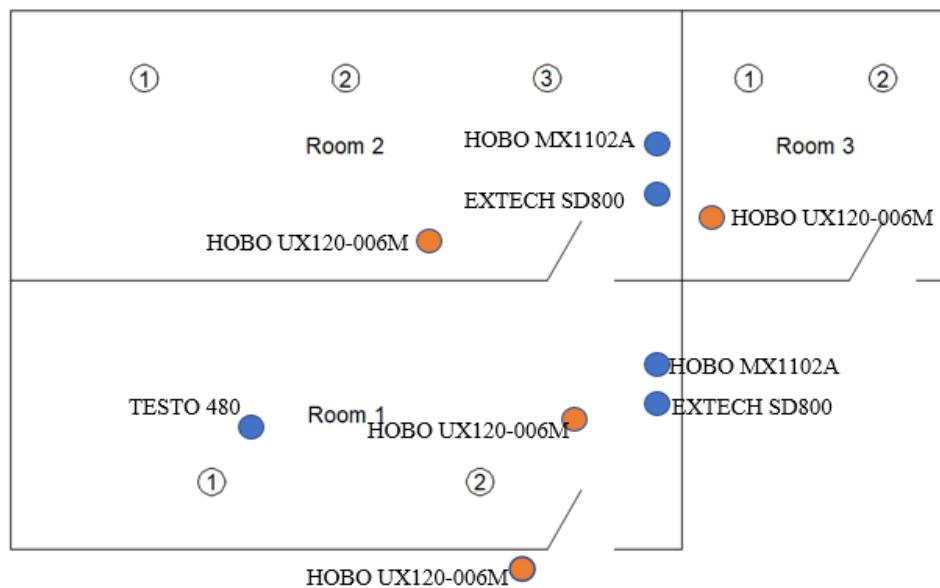


Figure 8. Schematic rooms layout in Case 1 (1 to 3 are room diffusers).

At the beginning of the study, performance of the ventilation system was measured. As a result, it was found that Room 1 has an air flow rate equal to $73 \text{ m}^3/\text{h}$. This room is constantly occupied presumably by four employees, but Room 2 has the minimum and maximum air flow rate equal to 127 and $320 \text{ m}^3/\text{h}$, respectively, (depending on a used speed of the fan). This room has 3 workplaces.

According to LVS EN 16798-1:2019 [49], Room 1 does not fulfil even the requirements of the worst, IV, comfort level, which is $21.6 \text{ m}^3/\text{h}$ per person or $86.4 \text{ m}^3/\text{h}$ per 4 persons.

At the minimum fan speed, the air flow in Room 2 is sufficient for comfort level III ($86.4 \text{ m}^3/\text{h}$ according standard against $127 \text{ m}^3/\text{h}$ in the room), but at the maximum fan speed, the air flow is significantly higher than required for comfort level I ($216 \text{ m}^3/\text{h}$ according to the standard against $320 \text{ m}^3/\text{h}$ in the room).

Figure 9 shows the total air flow rates for Room 1 and Room 2.

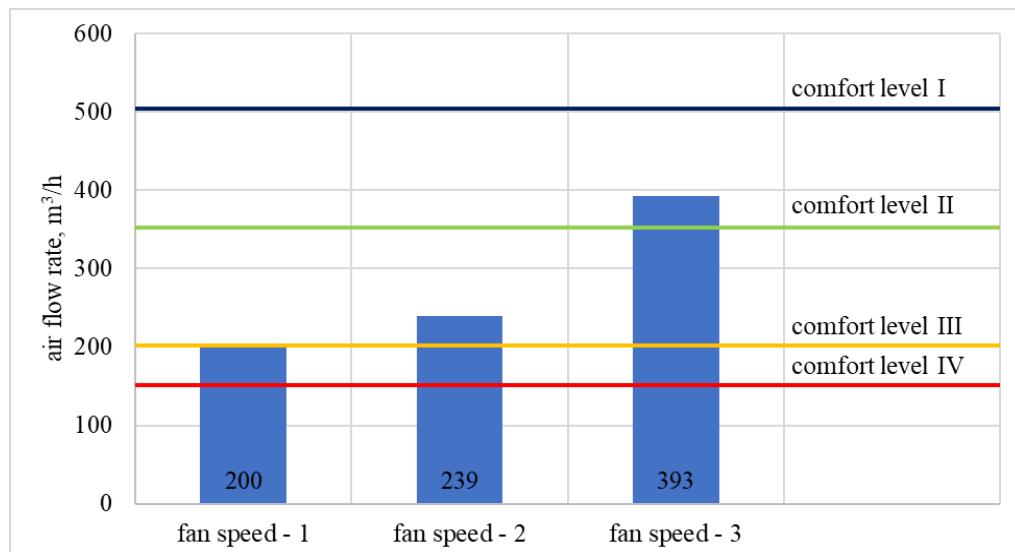


Figure 9. Total air flow rate for Room 1 and Room 2.

a. Preliminary IAQ measurement data

The first conclusion of the measurement is that it is vitally necessary to increase the air flow in Room 1.

In order to evaluate the working parameter in different CO₂ sensors (Extech and Testo models), both sensors were placed in the same location and were left to register CO₂ concentration for 8 days (Figure 10).

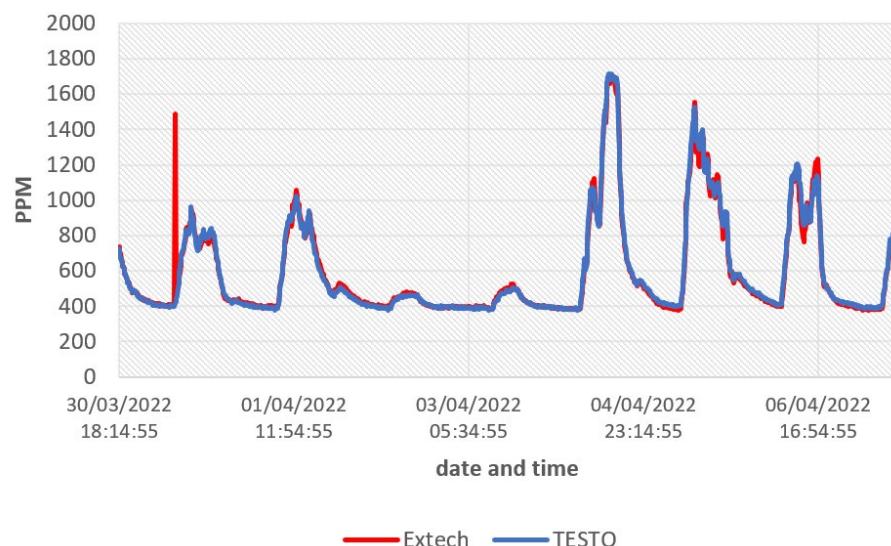


Figure 10. Comparison of measurement data of TESTO IAQ probe 0632 1543 and EXTECH SD800.

Both sensors were in use for several years and have not been calibrated. The next figure presents CO₂ measurements made by two identical brand-new sensors placed in the same room but in different locations. The room has four workstations and is used as a hall between other rooms.

As can be seen, both sensors showed almost equal results. The maximum difference between the sensors was 207 PPM. The measurements will be continued in order to get more data on CO₂ concentration distribution across the room. Current measurements were done during the summer when workers could open windows and leave them open during the night. Further research will cover more rooms with different occupancy profiles and will include wintertime when window opening is limited.

Further data presents CO₂ measurements done by completely brand-new logger-ONSET HOBO MX CO₂. One sensor was installed in an apartment without mechanical ventilation (Figure 11) and another in office building premises. Measurements in the apartment were performed in this report (Figure 12), as a case where CO₂ sensors provided misleading information which can cause incorrect management of HVAC systems.

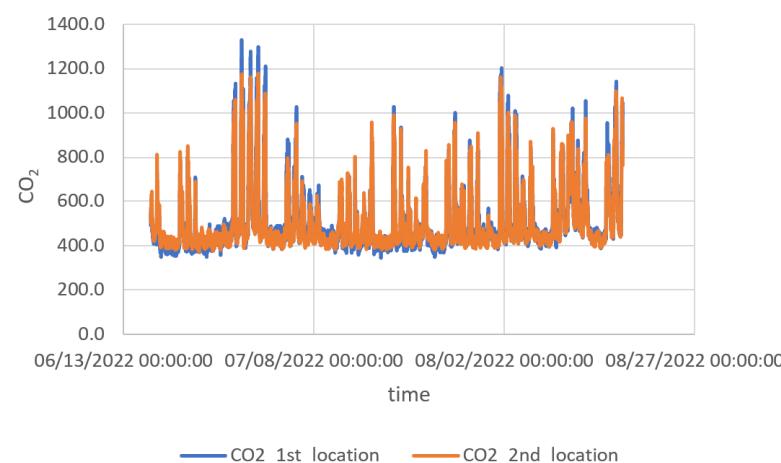


Figure 11. Comparison of CO₂ simultaneous measurements in two different locations.

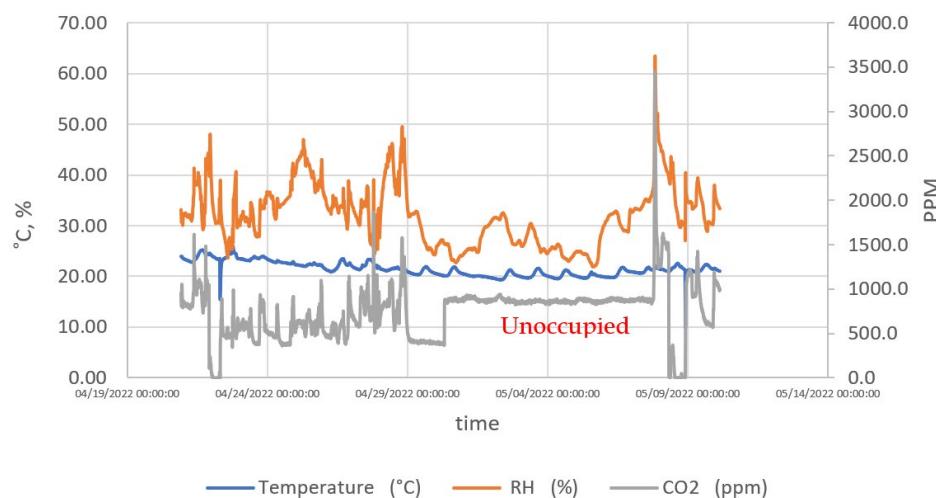


Figure 12. ONSET HOBO MX CO₂ logger monitoring data in the apartment bedroom without mechanical ventilation.

As can be seen, the new CO₂ logger has measured CO₂ concentration as 810 PPM (on average), while the room was unoccupied. Once the room was occupied, CO₂ readings dropped to 50 PPM. If this sensor were connected to BMS, the ventilation systems would be malfunctioning. The measurement failure was also identified during the other periods. Such a situation repeated three times during the measurements.

This issue should be investigated in more detail in future works. Probably this happens due to a failure during the sensor's automatic calibration, or it is impacted by other household pollutants. For example, cleaning sprays, fragrances, etc. Currently almost 90% of multiapartment buildings are not renovated and do not have any mechanical ventilation. The further possible retrofitting of existing buildings and installation of a mechanical system can significantly improve air exchange [50], as a result obtaining more precise measurements of CO₂ concentration.

The next two sensors were placed in the university staff room equipped with mechanical supply and exhaust ventilation. Figure 13 presents ONSET HOBO MX CO₂ loggers monitoring data in the university staff room with mechanical ventilation.

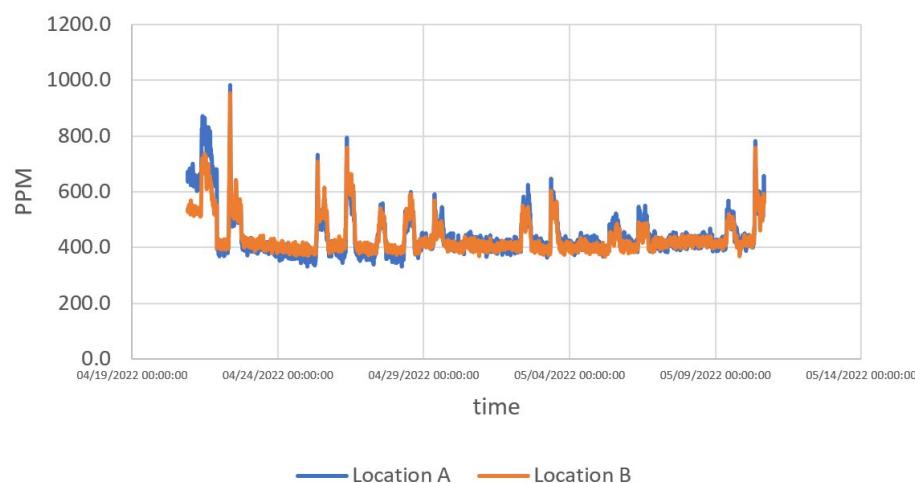


Figure 13. ONSET HOBO MX CO₂ loggers monitoring data in the university staff room with mechanical ventilation.

Both sensors were placed symmetrically close to the air exhaust terminal.

As some sensors may show incorrect information spatially in case people move and workspaces are not evenly distributed across the room, the HVAC systems can be managed by several sensors integrated in one platform (Figure 14).

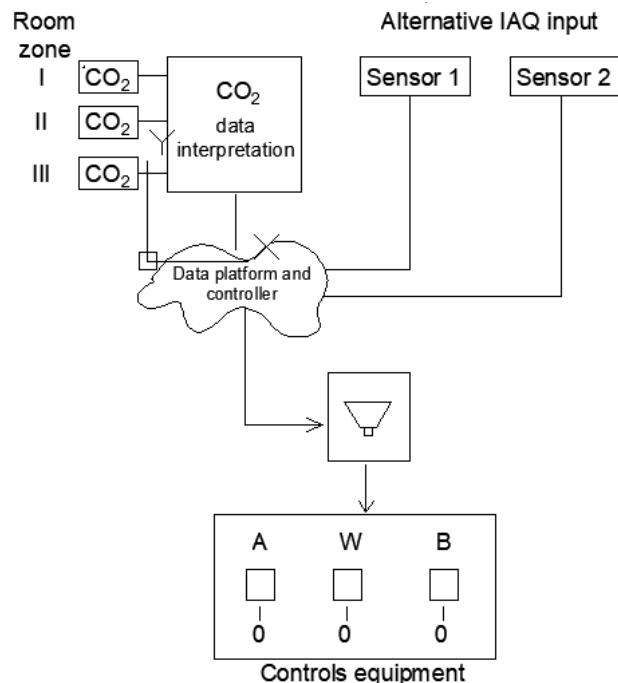


Figure 14. Overall structure of enhanced data management platform.

The enhanced systems will allow connection of several CO₂ sensors or any other types of sensors from one room. They can be programmed as one main sensor, and two as control sensors. For example, the weighted average can be set up taking into consideration the room load profile. In addition, it could be used to control the air supply in different room zones.

4. Discussion

The share of energy consumption, both electric and thermal energy, for ventilation needs could reach up to 60% in overall energy consumption. Thus, optimization of supply and exhaust air flows have a significant function in achieving reduction of energy consumption without the need to compromise on indoor air quality during occupation hours. One of the most popular and widely available methods is variable air flow based on indoor air CO₂ concentration. However, sensors must provide a precise measurement during the whole period of operation.

Nowadays, the sensor industry is growing rapidly. In order to ensure wide installation of sensors and to make it affordable for all types and sizes of ventilation systems, manufacturers are constantly looking for alternative low cost technologies. The new low-price sensors constantly appear on the market. In order to reduce maintenance costs, the majority of available sensors do not have a manual mechanical calibration option using the reference gases. Almost all sensors use the lowest CO₂ values as an outdoor air reference. Thus, they should be placed outdoor for calibration or the room should be unoccupied for some time. Consequently, some risk may occur if during automatic calibration the room is occupied.

However, performed measurements did not show any significant difference in CO₂ sensors within the same room, a future study should be done in order to investigate offices with different occupation profiles and ventilation types.

This study was performed during COVID-19 pandemic when ventilation systems were switched on to maximum capacities and the room occupancy was reduced.

There are several alternative indoor air cleaning solutions [51], which can help to reduce the concentration of CO₂ without increasing the ventilation rate.

5. Conclusions

Some professional sensors have a special calibration probe, while sensors widely available on the market are calibrated mainly by using general assumption on outdoor air CO₂ concentration. This has some limitations for practical application in rooms without mechanical ventilation and/or with a variable room occupancy profile.

According to existing studies, the most reliable sensors are temperature sensors. In the scope of this study, identical CO₂ sensors were used to measure CO₂ concentration in different rooms. In rooms with mechanical ventilation all CO₂ sensors have shown the same result and no failure was detected during the whole measurement period. While CO₂ sensors in rooms with natural ventilation has shown misleading readings when measured, CO₂ concentration has dropped to 50 PPM.

Since all NDIR sensors measure CO₂ concentration based on laser reflection, the future study will focus on household chemicals impact on CO₂ sensors measurement uncertainties. In addition, dust and candle burning can cause a misleading measurement.

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