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Mylonas, Angelos; Kazanci, Ongun Berk; Andersen, Rune K.; Olesen, Bjarne W.

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Capabilities and limitations of wireless CO₂, temperature and relative humidity sensors

Angelos Mylonas, Ongun Berk Kazanci*, Rune K. Andersen, Bjarne W. Olesen

International Centre for Indoor Environment and Energy – ICIEE, Department of Civil Engineering,
Technical University of Denmark, Nils Koppels Allé, Building 402, 2800 Kgs. Lyngby, Denmark

* Corresponding author. E-mail address: onka@byg.dtu.dk

ABSTRACT

Wireless indoor environment sensors that can measure temperature, relative humidity and CO₂ concentration have recently developed to a stage where they can be used in Building Management Systems (BMS) for building control or could be used to develop a remote commissioning process for buildings without BMS. This provides new opportunities for user involvement and fault detection but if the sensors are not accurate and reliable, it could introduce faults in itself.

The performance of different wireless indoor environment sensors in terms of their accuracy in the measurement of CO₂ concentration, temperature and humidity and the factors affecting their CO₂ measurement error were investigated. Six different types of sensors were tested in a climate chamber. The measurements of temperature, relative humidity and CO₂ concentrations obtained by the sensors

were compared to high precision reference instruments to quantify any deviations from the actual conditions. Linear regression was implemented to identify to what degree temperature, relative humidity, CO₂ concentration and calibration temperature of the CO₂ sensor affected the CO₂ measurement error of each device.

Determining the capabilities and limitations of these sensors makes it possible to quantify their effects on the HVAC system operation, energy use and indoor environment, if their measurements were used as inputs to the HVAC system.

The sensors performed satisfactorily in terms of temperature measurement and can be used to control the indoor temperature in buildings; however, this was not the case for measurements of relative humidity or CO₂ concentration.

Keywords: indoor environment monitoring; commissioning; wireless sensor; IoT; building control; indoor environmental quality

1 Introduction

There is an increasing focus on indoor environmental quality in buildings [1]. This has resulted in an expansion in the industry of wireless indoor environmental quality monitors. Most of them are able to measure CO₂ concentration, temperature and relative humidity. It would be useful if these sensors could be used to improve the commissioning process and control of indoor environmental quality (IEQ), especially in smaller buildings without Building Management Systems (BMS) or if they could replace the wired sensors currently used in BMS, which are often expensive to install [2]. However, before implementing these sensors in buildings, it is imperative that their measurement accuracy with respect to temperature, relative humidity and CO₂ concentration, and the factors affecting the precision of the CO₂ measurement values should be quantified. Menzel et al. [3] showed how well wireless sensors can be integrated into existing and future BMS for improving building energy performance.

Recently, Parkinson et al. [4] described the development and performance of a wireless, low-cost IEQ monitor called SAMBA. It consists of sensors that can continuously measure air temperature, relative humidity, globe temperature, air speed, sound pressure level, illuminance, CO₂ concentration (by means of NDIR technology), carbon monoxide, formaldehyde and total volatile organic compounds. It offers real time visualization of all measured IEQ parameters via an online platform. It is argued that such a tool can be very useful for building owners, facility managers, tenants and occupants. In a subsequent study, Parkinson et al. [5] examined the performance of 100 SAMBA devices regarding thermal comfort, indoor air quality, lighting and acoustics by performing laboratory tests. Furthermore, a Monte Carlo simulation analysis was implemented to determine the ability of SAMBA to correctly classify thermal comfort as a binary outcome based on the readings of 100 SAMBA devices distributed in 24 office buildings in Sydney, measuring continuously for three months.

Kolarik and Olesen [6] studied the influence of measurement uncertainty on the classification of the thermal environment in buildings based on field measurements and Kazanci et al. [7], recently reported on a set of field measurements from buildings with Thermally Active Building Systems. Both of these studies could have benefited from wireless indoor environment sensors for carrying out the field measurements; however, determination of the accuracy of such measurements is a crucial factor if wireless indoor environment sensors are to be used in Building Management Systems.

One of the most common ways of monitoring CO₂ concentration in the indoor environment is by using nondispersive infrared (NDIR) sensors. According to Yi et al. [8], NDIR sensors are characterized by long-term stability, high accuracy and low power consumption. However, variation of ambient temperature is known to influence the NDIR overall precision [9]. After comparing four different small commercial CO₂ sensor models, Yasuda et al. [10] concluded that calibration is necessary for improving the CO₂ measurement error of the sensors.

For improving the measurement accuracy of the sensors due to temperature, Park et al. [11] developed an NDIR CO₂ gas sensor with automatic temperature compensation and amplification circuits for HVAC systems. It was found that the sensor was unaffected by temperature variations, showing ± 30 ppm error at 1000 ppm and ± 50 ppm error at 2000 ppm of CO₂ concentration in the range 10-40 °C. Hyun et al.

[12] studied the effects of the temperature compensation method in combination with different reflector materials (chrome and gold), and found that gold-plating the optical chamber in combination with temperature compensation led to higher accuracy.

Yi [13] reported that the output of a CO₂ sensor depended on two variables: temperature and CO₂ gas concentration. Marinov et al. [14] showed that temperature and pressure led to significant variations in a sensor's readings. Another study by Petersen et al. [15] compared two commercial low-cost, NDIR CO₂ sensors at different temperatures and CO₂ concentrations. They found a relationship between temperature and CO₂ measurement error but since they only investigated two sensor brands, it is not possible to determine if the relationship is a general property of NDIR sensors. In another study by Mylonas et al. [16], the accuracy of the temperature, relative humidity and CO₂ concentration measurements of different wireless IEQ sensors was determined. However, the authors reported only the observed average measurement errors of the different sensors and did not analyse how the CO₂ concentration errors were affected by other variables.

Fisk et al. [17] studied the accuracy of 44 NDIR CO₂ sensors. The sensors were located in nine commercial buildings to evaluate the performance of the CO₂ sensors in the field. These authors concluded that there is a need for more accurate CO₂ sensors and that better calibration procedures might lead to better performance. Pandey et al. [18] assessed the CO₂ measurement error of two different types of NDIR sensors from different manufacturers. Three identical units of each of the two selected sensor types were tested. All devices were exposed to CO₂ concentrations of 0, 500 and 1000 ppm. The study concluded that NDIR sensors are highly reliable and able to achieve an accuracy of approximately 5%. In another study, Pandey and Kim [19] assessed the relative performance of NDIR sensors in continuous real-time monitoring of CO₂ concentrations. The sensors were located in open-air conditions in a laboratory. The sensors acquired data every three seconds for 304 hours. Based on a correlation analysis and the relative standard error analysis of the sensors, the authors concluded that NDIR sensors are sufficiently reliable and stable.

Fahlen et al. [20] studied the performance of one photo-acoustic type and one infrared spectroscopy type CO₂ sensor in long term tests and laboratory tests. It was found that the CO₂ measurement error was

normally around ± 50 ppm when exposed to a concentration of 1000 ppm and -300 ppm at 2000 ppm of CO₂ concentration. Shrestha and Maxwell [21] tested and evaluated the accuracy, linearity, repeatability, hysteresis, and humidity-temperature-pressure sensitivity of the most commonly used NDIR CO₂ sensors in HVAC systems. Significant variations in the performance of sensors of the same type were discovered. In the second part of a 4-part study, Shrestha and Maxwell [22] compared the findings of their previous study to the manufacturers' specifications. The sensors (45 in total, 15 different models, three of each model) were tested at 40% relative humidity, 22.8 °C, 101.35 kPa pressure and at five CO₂ concentrations (400, 750, 1100, 1450 and 1800 ppm). The results showed that none of the sensor models achieved the accuracy claimed by the manufacturer in all three sensors of the same model for all the test conditions. In some cases, none of the three sensors of the same type met the manufacturer's specifications. The same authors [23] studied wall-mounted NDIR sensors to determine their sensitivity to humidity, temperature and pressure. The results showed that temperature and pressure variation influenced the CO₂ measurement error of the sensors. The authors also indicated that field calibration was another factor influencing the sensitivity of NDIR CO₂ sensors. In the third part of the study, Shrestha and Maxwell [23] examined the impact of each parameter (relative humidity, temperature and pressure) on the CO₂ measurement accuracy of each sensor. CO₂ concentration during the experiments was 1100 ppm. The results showed that only three sensors were sensitive to humidity variations and that effects of temperature and pressure variation on the accuracy of NDIR CO₂ sensors are inevitable. In the last part of the study, all 45 sensors were tested every four months under steady state conditions of relative humidity, temperature, pressure and CO₂ concentration throughout one year to determine the effects of ageing [24]. It was found that the ageing affected each sensor type in a different way. Martin [25] tested several identical low-cost NDIR sensors in laboratory and ambient air conditions and reported that all of the sensors achieved the accuracy of ± 30 ppm or $\pm 3\%$ of reading claimed by the manufacturer. The literature and developments in this field show an increasing interest in wireless IEQ sensors for measuring CO₂ concentration, temperature and relative humidity. There are several factors that affect the accuracy of IEQ sensors and each IEQ sensor is affected differently by these factors. As we enter an IoT era and before wireless IEQ sensors are installed in large numbers and become a standard solution in

new and existing buildings, it is crucial that their accuracy under different conditions is known. The main objective of this experimental study was therefore to determine the factors affecting the CO₂ concentration measurement error of six different types of commercially available wireless NDIR sensors. Several detailed experiments were conducted to evaluate the accuracy of the CO₂ concentration measurements obtained from each indoor environmental quality monitoring device. Four parameters (temperature, humidity, CO₂ concentration and the temperature at which the CO₂ sensor of each unit was calibrated) were examined in order to assess how they affected the accuracy of the CO₂ concentration measurement. Additionally, the accuracy of the temperature, the relative humidity and the CO₂ concentration measurements were quantified. The intention was to determine whether commercially available units are mature enough to implement in building controls on a large scale.

2 Methodology

2.1 Selection procedure of the wireless indoor environment sensors

A market search was conducted to determine the commercially available wireless indoor environmental sensors to be tested and forty-four different sensors were identified.

Based on a number of criteria (temperature, relative humidity and CO₂ concentration measurement capability, internet connectivity, real-time remote tracking possibility, ease of access to measured data, availability and price), the list was narrowed down to six sensor types, each from a different manufacturer (Table 1). Three identical examples of each of the six selected sensor types were tested in order to be able to draw robust conclusions for each sensor. Pandey et al. [18] and Shrestha and Maxwell [22] used a similar approach and also tested three of each sensor type.

All modules of type B, C, E and F were factory new and were used for the first time during this study. However, sensor types A, D1 and D2 were not new and they had been used previously in similar experiments [15].

Table 1 summarizes the temperature, relative humidity, CO₂ concentration measurement ranges and accuracies, price, CO₂ sensor calibration protocol, and power consumption characteristics of the chosen

sensors as provided by their manufacturers. An overview of some additional technical characteristics of each device is provided in the Appendix

Table 1: Basic characteristics specified by the manufacturers of the examined sensors.

Sensors	Temperature (range and accuracy)	Relative Humidity [%] (range and accuracy)	CO ₂ concentration [ppm] (range and accuracy)	Price [€]	CO ₂ sensor Calibration***	Power consumption [W]
A	-20 – +80 °C, ±0.3 K	0 – 95, ±2	380-10000, ±30	513	Auto&Manual	0.1
B	-40 – +100 °C, ±0.3 K	0 – 100, ±3	0-3000, ±30	304	Auto&Manual	0.5-0.8
C	-10 – +85 °C, ±0.4 K	0 – 100, ±3	400-2000, ±50	380	Auto&Manual	0.8
D1	0 – +50 °C, ±0.3 K	0 – 100, ±3	0-5000, ±50	162	Auto&Manual	Up to 2.8
D2*	0 – +50 °C, ±0.3 K	0 – 100, ±3	0-5000, ±50	70	Auto	0.8
E	-10 – +40 °C, ±10%**	0 – 100, ±10	400-5000, ±50	277	Auto	5.0
F	-40 – +85 °C, ±0.5 K	0 – 100, ±3	0-10000, ±50	270	Auto	0.9-1.5

* The difference between Sensors D1 and D2 is that D1 can measure Noise and Pressure, while D2 cannot. Also, D2 operates on battery power, while D1 needs power from a plug.

** The manufacturer indicated an accuracy of ±10% for temperature measurements.

***The calibration was a single point calibration, aligning the sensor output with outdoor CO₂ concentration (typically assumed to be 400 ppm)

2.2 Experimental procedure

The experiments were carried out in a climate chamber at the International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark. The climate chamber had the dimensions of 3.6 m x 2.5 m x 2.5 m (L x W x H) and all surfaces were stainless steel. The

temperature and relative humidity in the climate chamber could be adjusted to between 10-40°C and 10-90%, respectively. It was possible to provide up to 70 air changes per hour by displacement ventilation from the floor of the climate chamber. The air was supplied into the climate chamber from the whole floor surface, through perforated metal plates. The chamber was well insulated from the surrounding environment and it was designed so the air temperature and the mean radiant temperature were almost identical at steady-state.

The sensors were all inside the chamber at the same time. Their respective positions (i.e. horizontal or vertical) followed the recommendations from the manufacturers. CO₂ was dosed through the supply duct and four fans were used, one in each corner of the chamber, to ensure full-mixing and uniform CO₂ concentration in the chamber. The measurements were carried out under strictly controlled steady-state conditions of temperature and CO₂ concentration. In each combination of temperature and CO₂ concentration, the range within which the temperature, CO₂ concentration and relative humidity varied was kept below 0.16 K, 57 ppm and 4%, respectively, for at least two hours. This ensured that a representative amount of data from each device was collected for the analysis. Figure 1 shows the experimental setup of the climate chamber. In Figure 1, the red arrows indicate the position of the tubes taking air samples for CO₂ reference instrument. The yellow arrows indicate the position of the reference temperature and relative humidity sensors.

Figure 1: Chamber experimental setup

The purpose of the experiment was to determine the effects of different parameters (i.e. temperature, CO₂ concentration, relative humidity and calibration temperature) on the CO₂ measurement error of each unit and to quantify the measurement errors in temperature, relative humidity and CO₂ concentration obtained by each sensor.

Relative humidity was measured but not controlled. Additionally, the effect of the calibration temperature and of different humidity levels on the accuracy of the CO₂ measurements was examined.

As it was not possible to control the humidity level in the chamber, the sensors' humidity readings were compared to the reference instrument's humidity readings at every single recording moment. However, the highest variation in relative humidity within an experimental combination of temperature and CO₂ concentration was 4%.

The experiment took place in three phases. The first phase examined the impact of different temperatures and CO₂ concentration levels on the accuracy of the CO₂ sensors. In the second phase, the effect of different calibration temperatures of the CO₂ sensor on its measurement error was examined. During the third and last phase, the influence of the humidity level on the CO₂ measurement error was examined.

During the first phase, the CO₂ sensors that could be manually calibrated were calibrated at 20 °C before the measurements. Before the experiments, all devices were installed in an open-plan indoor space with low occupancy and high ventilation rate for a period of more than 3 weeks. After manual calibration, all sensors were left for nine days in the climate chamber ventilated with outdoor air at 20 °C, to complete the self-calibration process of the sensors that did not have a manual calibration option.

During the second phase, only the devices that could be manually calibrated were considered and the devices were calibrated at 20 °C. The CO₂ sensors were manually calibrated at 30 °C to investigate whether the calibration temperature affected the CO₂ measurement error. The CO₂ sensors were then exposed to 20 °C and 30 °C after being calibrated at 30 °C.

In the third phase, the effect of the humidity level on the CO₂ measurement error was examined. Even though the relative humidity was not controlled, the experiments in Phase 1 and 2 were conducted between 5%-50% relative humidity. A higher level of humidity was used in Phase 3 to determine whether it affected the measurement accuracy of the CO₂ sensors. A humidifier was used to increase the relative

humidity. The experiments were conducted at 20 °C, 88% relative humidity, and at a CO₂ concentration of 400 ppm and 1600 ppm. All sensors, both manually but automatically self-calibrated (i.e. the sensor assumed the lowest measured CO₂ concentration in the previous one or two weeks to be the outdoor CO₂ concentration), were evaluated. Manual calibration was performed at 20 °C in this phase.

Table 2 summarizes the experimental conditions in the first and second phases.

Table 2: Test conditions in the chamber during the first and second phases of the experimental procedure. Relative humidity was not controlled but varied less than ± 4 %-points in each test condition.

Test Temperatures [°C]	Test CO ₂ Concentrations [ppm]				
	400	800	1200	1600	1930
Calibration Temperature of CO₂ sensors at 20 °C					
16	33% RH*	38% RH	51% RH	42% RH	23% RH
20	28% RH	27% RH	29% RH	35% RH	18% RH
25	22% RH	22% RH	19% RH	11% RH	7% RH
30	8% RH	8% RH	8% RH	13% RH	5% RH
Calibration Temperature of CO₂ sensors at 30 °C					
20	28% RH	Not conducted	Not conducted	Not conducted	18% RH
30	8% RH	8% RH	8% RH	13% RH	5% RH

*: The relative humidity values indicated in the table are the average relative humidity of all the measurements of the reference instrument during one test combination of temperature and CO₂ concentration.

For the experimental conditions, 16°C and 30°C were chosen as extreme indoor temperatures. 16°C is the lowest temperature in Category 2 of EN 15251:2007 [26] for different building types. 30°C could be

encountered under extreme conditions indoors but this selection did not follow a strict standard.

The CO₂ concentration levels also followed the values provided in EN 15251. 400 ppm is assumed to be the CO₂ concentration outdoors, and 1200 ppm is the limit of Category 3 of EN 15251. 800 ppm was chosen to be in the middle of this range.

Even though 2000 ppm can sometimes be exceeded in practice, we assumed this to be the highest CO₂ concentration to test the sensors, also because this was the highest CO₂ concentration in the measurement range of one of the sensors (C).

During the experiments, it was found that 1930 ppm was the highest steady state CO₂ concentration that could be achieved in the chamber. Above that concentration, it was not possible to achieve steady state conditions due to fluctuations in the CO₂ dosing system that occurred at high flows. 1600 ppm was chosen as the mid-point of the range from 1200 ppm and 2000 (1930) ppm.

The measurements of temperature, relative humidity and CO₂ concentration were compared to measurements from the reference instruments to quantify the deviations from the actual conditions in the climate chamber. The air temperature, relative humidity and CO₂ concentration in the climate chamber were measured with high accuracy reference instruments. Air temperature was measured with a high precision thermometer with an accuracy of ± 0.03 K within the range of -100 to 150 °C. The reference relative humidity sensor had an accuracy of $\pm 1.5\%$ -points within the range of 0 to 100%. The reference CO₂ concentration was measured at four locations in the chamber with a photoacoustic multi-gas analyser with an error (specified by the manufacturer) of $\pm 3\%$ of the reading. All reference instruments were calibrated by their manufacturers prior to the experiments and all measurements were carried out well before the expiration date of the reference instruments' calibration certificates.

In order to find the measurement error of each sensor for temperature, CO₂ concentration and relative humidity, the measured values were subtracted from the values measured by the reference instruments (i.e. a positive measurement error indicates that the sensor was measuring lower values than the reference instrument, and vice versa).

Tables A2 and A3 in Appendix summarise the total number of measurements made by all the sensors of each type, in all test temperatures and CO₂ concentrations.

2.3 Linear Regression Analysis

Linear regression analysis was applied to investigate how the CO₂ measurement error of an indoor environment sensor varied as a function of the other measured factors. The factors considered were temperature, relative humidity, CO₂ concentration and calibration temperature. The CO₂ error could be represented by a multiple variable linear regression equation. For the sensor types that had a manual calibration option, the CO₂ error was represented by an equation in the form of Equation (1) and for the sensor types with automatic self-calibration, the multiple linear regression was in the form of Equation (2).

$$\text{CO}_2\text{error} = \text{Temperature} \cdot B + \text{CO}_2\text{con} \cdot C + \text{RH} \cdot D + \text{CalibrationTemperature} \cdot E + \text{constant} \quad (1)$$

$$\text{CO}_2\text{error} = \text{Temperature} \cdot B + \text{CO}_2\text{con} \cdot C + \text{RH} \cdot D + \text{constant} \quad (2)$$

where, B, C, D and E are coefficients, and Temperature, CO₂con, RH and CalibrationTemperature are normalized variables from each condition.

The variables were normalized so that the coefficients could be compared directly. The variable normalization was performed by scaling each feature to a range between the minimum and maximum value of each variable observed during all experimental conditions. This normalization is given by Equation (3).

$$X_{\text{norm}} = (X - X_{\text{min}}) / (X_{\text{max}} - X_{\text{min}}) \quad (3)$$

Where X_{norm} is the normalized coefficient of each variable tested (temperature, CO₂ concentration, relative humidity and calibration temperature).

3 Results

3.1 *Temperature, relative humidity and CO₂ concentration measurement error of the sensors*

Table 3 shows the minimum and maximum errors, defined as the differences between the measurements from all sensors of each type and the reference instruments (Reference instrument value – sensor value).

Table 3: Max positive and negative observed measurement errors of all sensors.

Temperature [K]	Relative Humidity [%-points]	CO ₂ concentration [ppm]
A1, -0.3 – +0.0 **	A1, -0.8 – +3.9	A1, -271 – +161
A2, -0.2 – +0.1	A2, -1.5 – +3.7	A2, -289 – +26
A3, -0.2 – +0.1	A3, -2.1 – +4.2	A3, -310 – +19
B1, -0.2 – +0.3	B1, -0.7 – +4.2	B1, -413 – +113
B2, 0.0 – +0.5 *	B2, -2.3 – +1.7	B2, -310 – +18
B3, 0.0 – +0.5 *	B3, -1.8 – +2.7	B3, -392 – +24
C1, -0.1 – +0.2	C1, -6.1 – +9.2	C1, -235 – +361
C2, -0.4 – +0.2	C2, -4.8 – +8.4	C2, -290 – +294
C3, -0.3 – +0.1	C3, -7.1 – +7.4	C3, -293 – +207
D1a, -0.3 – +0.3	D1a, -28.9 – +5	D1a, -135 – +401
D1b, -0.7 – -0.3 **	D1b, -15.9 – +10.5	D1b, -99 – +410
D2a, 0.0 – +0.3 *	D2a, -38.9 – +4.7	D2a, +530 – +4586 ***
D2b, -0.2 – +0.3	D2b, -36.9 – +5.5	D2b, -25 – +798
E1, -1.9 – +0.6	E1, -1.9 – +6	E1, -271 – +41
E2, -1.7 – +0.8	E2, -1.9 – +6.5	E2, -268 – +55
E3, -1.8 – +0.7	E3, -4.3 – +7.6	E3, -165 – +41
F1, 0.4 – +1.5 *	F1, -6.3 – +5	F1, -53 – +328
F2, 0.1 – +1.4 *	F2, -7.1 – +1.6	F2, -161 – +276

*No values below the actual temperatures were recorded.

**No values above the actual temperatures were recorded.

***No values below the actual CO₂ concentration were recorded.

The temperature measurement errors of Sensors A, B, D2 and C were mostly within the range specified by the manufacturers. However, the temperature measurement of Sensors D1, F or E, did not achieve the accuracy stated by the manufacturers.

Table 4 shows the sensors' temperature measurement errors compared to the required and desirable air temperature accuracies given in EN ISO 7726:2001 [27] (i.e. ± 0.5 K and ± 0.2 K, respectively, in the range 10-40 °C).

Table 4: Temperature characteristics of measuring instruments

Sensors	Sensors' temperature error [K]	Air temperature accuracies	
		Required (± 0.5 K)	Desirable (± 0.2 K)
A1	-0.3 – +0.0	✓	✗
A2	-0.2 – +0.1	✓	✓
A3	-0.2 – +0.1	✓	✓
B1	-0.2 – +0.3	✓	✗
B2	0.0 – +0.5	✓	✗
B3	0.0 – +0.5	✓	✗
C1	-0.1 – +0.2	✓	✓
C2	-0.4 – +0.2	✓	✗
C3	-0.3 – +0.1	✓	✗
D1a	-0.3 – +0.3	✓	✗
D1b	-0.7 – -0.3	✗	✗
D2a	0.0 – +0.3	✓	✗
D2b	-1.9 – +0.6	✗	✗
E1	-1.9 – +0.6	✗	✗
E2	-1.7 – +0.8	✗	✗
E3	-1.8 – +0.7	✗	✗
F1	0.4 – +1.5	✗	✗
F2	0.1 – +1.4	✗	✗

3.2 Effect of temperature and level of CO₂ concentration on the sensors' CO₂ measurement error

During the first phase of the experiments, the impact of different temperatures and CO₂ concentration levels on the CO₂ measurement error of each sensor was examined. The manual calibration feature was not available in all devices. Thus, units A, B, C and D1 that can be manually calibrated were calibrated at 20 °C. The rest of the sensors (D2, E and F) were automatically self-calibrated as described in the Methods section.

In Figures 2 – 6, boxplots of the observed errors of each sensor type are given. Each boxplot contains the median measured error, upper and lower quartiles, and highest and lowest values. Only the sensors whose measurement error was influenced by the temperature and by the CO₂ concentration level are shown.

Figure 2: CO₂ measurement error of sensor A, at all combinations of temperature and CO₂ concentration

In Figure 3, some of the measurements from sensor type B were lost and are not shown. More specifically, the sensor did not upload data at 16 °C, at concentrations of 800 ppm, 1200 ppm and 1600 ppm, and at 20 °C and 400 ppm of CO₂ concentration. The reason for this data loss has not been discovered.

Figure 3: CO₂ measurement error of sensor B, at all combinations of temperature and CO₂ concentration

Figure 4: CO₂ measurement error of sensor D1, at all combinations of temperature and CO₂ concentration

Figure 5: CO₂ measurement error of sensor E, at all combinations of temperature and CO₂ concentration

The error in the CO₂ concentration in Sensors A, B and E (Figure 2, Figure 3 and Figure 5, respectively) increased with increasing level of CO₂ concentration. This CO₂ concentration dependency was observed for all steady-state conditions and the measured CO₂ concentration was lower than the value recorded by the reference instrument.

Figure 6: CO₂ measurement error of sensor F, at all combinations of temperature and CO₂ concentration

At high temperatures, Sensors D1 and F recorded higher levels of CO₂ concentration than the reference instrument. Figure 7 shows the average CO₂ relative error of all sensors, at all CO₂ concentrations, when calibrated at 20 °C.

Figure 7: Average CO₂ Relative Error of all sensors, at all CO₂ concentrations when calibrated at 20 °C

3.3 Calibration temperature - CO₂ accuracy interaction

This phase of the experiment examined whether the temperature at which the CO₂ sensor of each of the IEQ sensors was calibrated, had any impact on the CO₂ measurement error. The manual calibration component was not available in all units, so only units A, B, C and D1 were evaluated. Calibration information concerning Sensors D2, E and F that can only be automatically self-calibrated was not provided by the manufacturers. These sensors were calibrated at 20 °C and 30 °C. The test conditions were all combinations of 30 °C and 400, 800, 1200, 1600 and 1930 ppm CO₂ concentration.

Figure 8 and Figure 9 show the results for the CO₂ sensors that were affected the most by the calibration temperature.

Figure 8: Impact of calibration temperature on the CO₂ measurement error of sensor type B

Figure 9: Impact of calibration temperature on the CO₂ measurement error of sensor type C

The error in the CO₂ concentration measurement for sensor type B (Figure 8) increased significantly with increasing calibration temperature for all steady-state conditions. However, for sensor type C, the CO₂ measurement error decreased with increasing calibration temperature (Figure 9).

Figure 10 shows the average CO₂ relative error of manually calibrated sensors, at all CO₂ concentrations, when calibrated at 30 °C. Figure 11 shows the relative error of manually calibrated sensors when tested at 20 °C, and 400 ppm and 1930 ppm CO₂ concentration. Figure 12 shows the average CO₂ relative error of manually calibrated sensors when tested at 30 °C, and 400 ppm and 1930 ppm CO₂ concentration.

Figure 10: Average CO₂ Relative Error of manually calibrated sensors when Calibrated at 30 °C

Figure 11: Average CO₂ Relative Error of manually calibrated sensors when tested at 20 °C, and 400 ppm and 1930 ppm CO₂ concentration.

Figure 12: Average CO₂ Relative Error of manually calibrated sensors when tested at 30 °C, and 400 ppm and 1930 ppm CO₂ concentration.

3.4 Relative humidity - CO₂ accuracy interaction

In this section, the effects of relative humidity on the sensors' CO₂ measurement error were studied. The humidity level in the climate chamber was measured but not controlled and it was observed that all the measurements in the previous two stages were conducted between 5%-50% relative humidity. Throughout this last phase of the experiments, a relative humidity level of 88% was achieved and maintained in the climate chamber. The test conditions were all combinations of 88% relative humidity, 20 °C temperature, and, 400 ppm and 1600 ppm of CO₂ concentration. Sensors, A, B, C and D1 were calibrated at 20 °C.

In Figure 13, the impact of the relative humidity level on sensor type C is shown.

Figure 13: Impact of relative humidity levels on the CO₂ measurement error of the type C sensors.

An effect of relative humidity on the CO₂ measurement error of type C sensors was observed. The CO₂ measurement error of all three type C sensors increased with increasing relative humidity. For the other types of sensors, no effect of relative humidity was observed. Figure 14 shows the average CO₂ relative error of all sensors at 88% relative humidity, 20 °C and all CO₂ concentrations. Figure 15 shows the average CO₂ relative error of all sensors due to the different levels of relative humidity.

Figure 14: Average CO₂ Relative Error of all sensors at 88% relative humidity and 20 °C.

Figure 15: Average CO₂ Relative Error of all sensors due to the different levels of relative humidity.

3.5 Relative humidity results

The highest deviations (below and above the readings of the reference instrument) among all the relative humidity levels that occurred during all the experiments are shown in Table 3.

Except for sensor type E, none of the units achieved the manufacturers' stated accuracy. Significantly higher deviations from the actual relative humidity levels were observed for Sensors D1 and D2.

3.6 *Linear Regression Analysis results*

As defined by Winter [28], none of the assumptions of the multiple linear regression analysis was violated, leading to the conclusion that the CO₂ error of the sensors could be modelled by a multiple variable linear model. Table 5 shows the coefficients estimated from the sample data in the Multiple Linear Regression analysis. Values in bold indicate the factor affecting the CO₂ accuracy of each sensor the most.

Table 5: Coefficients of each variable for all sensors. Values in bold indicate the most influential variable on the CO₂ concentration measurement error.

Sensors	Temperature	CO ₂ Concentration	Relative Humidity	Calibration Temperature	Constant	R-Squared
A1	-95.7	170.7	-77.2	34.9	-15.1	0.45
A2	-4.60	177.0	14.01	73.3	29.5	0.85
A3	-10.1	190.3	5.64	73.3	33.2	0.88
B1	8.18	179.3	-5.18	156.9	14.8	0.87
B2	-8.39	167.1	-16.8	99.3	54.3	0.87
B3	26.1	200.2	-8.27	61.15	18.9	0.8
C1	-33.8	22.77	-353.1	-138.8	169.4	0.53
C2	1.73	28.36	-321.5	-182.4	165.6	0.65
C3	47.7	11.26	-165.4	-109.8	80.47	0.41
D1a	-365.1	129.8	-48.1	14.2	184.3	0.92
D1b	-318.3	-161.7	-67.37	57.51	102.3	0.82
D2a	-1127.7	-336.5	-3475.8	-	417.8	0.58
D2b	-566.36	-439.01	-111.9	-	176.1	0.95
E1	20.54	75.34	40.33	-	1.71	0.64
E2	10	84.38	15.64	-	8.08	0.67
E3	14.78	103.4	31.32	-	4.17	0.77
F1	17.3	79.1	-100.22	-	-40.04	0.43
F2	-140.1	28.27	53.19	-	-38.45	0.55

4 Discussion

4.1 *Sensors' CO₂ accuracy and dependency*

None of the sensors achieved the CO₂ accuracy stated by the manufacturers (± 30 or ± 50 ppm). The precision of the CO₂ measurements of different indoor environment sensors was dependent on different factors. The errors of Sensors A, B and E, which all use the same CO₂ sensor type, were mostly dependent on the CO₂ concentration. The measurement error of sensors A, B and E was in general not dependent on temperature. The CO₂ measurement error of Sensors A, B and E increased with increasing CO₂ concentration. The error of Sensors D1, D2 and F increased with increasing temperature.

Relative humidity was the main variable affecting the CO₂ measurement error of Sensor C. Marinov et al. [14] identified humidity variations as one of the causes of reduced accuracy and long-term stability of NDIR CO₂ sensors. These findings were confirmed by the Linear Regression Analysis of the available data.

4.2 *Temperature and relative humidity accuracy*

The temperature and relative humidity measurements made by the sensors could impact not only the thermal comfort of occupants but also the indoor environment and energy use of the building, if their Building Management System were to be controlled by such devices.

The results show that the temperature measurement errors of Sensors A, B, D2 and C were within the acceptable ranges stipulated by EN ISO 7726 and mostly within the accuracies stated by the manufacturers. Sensors D1, E and F should be considered carefully if they are to be used for temperature control. They exhibited large measurement errors, exceeding the required (± 0.5 K) air temperature accuracy required by EN ISO 7726 in all test conditions.

As it was not possible to control the relative humidity in the chamber, the sensor measurements were compared with the reference instrument's readings at every single recording moment. Only the three type E sensors achieved the manufacturer's stated accuracy ($\pm 10\%$). Sensor types D1 and D2, as shown in

Table 3, exhibited high relative humidity measurement error and should be considered carefully for indoor environmental monitoring or control.

4.3. Limitations of the present study

It should be noted that the experiments could have been improved further if it had been possible to control the humidity level throughout the experiment.

The calibration temperature of the CO₂ sensor influenced the measurement error of each sensor. However, information regarding the calibration of the CO₂ sensor of the devices that can only be automatically self-calibrated was not provided by the manufacturers.

During the experiments, some devices exhibited considerable deviation from the actual values of CO₂ concentration and relative humidity. Sensors D1 and D2 exhibited large errors in relative humidity and should be considered carefully (even though the devices had been used in other research and were not factory new, no mechanical damage was observed prior to or during the experiments).

4.4 General discussions

If these sensors were to be used for commissioning or were to replace BMS sensors in the future, their effects on heating, cooling and ventilation system operation, indoor environmental control and on energy use should be considered as they will have different effects on these aspects. The results should be studied in relation to the accuracies and capabilities of the BMS sensors that are currently used in buildings.

This study was carried out under steady-state conditions; however, these sensors will normally be used under dynamic conditions in buildings. Therefore, it would be desirable for future studies to study the dynamic behaviour of these sensors. This was not done in the current study due to time and budget limitations.

The measurement accuracies of the sensors (for air temperature) could be compared to the required and

desirable accuracies described in EN ISO 7726. However, it should be noted that although the manufacturers claim that they measure air temperature, the air temperature sensors used in these sensors are inside a casing that is inevitably influenced by the radiant temperature, as it is not aspirated, so they do not directly measure the air temperature.

In addition to the parameters investigated in this study, other parameters such as internet connectivity, real-time tracking, ease of access to measured data, availability and price should also be considered before the final selection of the sensors.

If these wireless sensors were to be used to replace the hard-wired sensors in existing Building Management Systems, it is critical that their ability to acquire and store measurement data even when network connectivity problems occur can be ensured for a specific period.

It should be noted that the main aim of this study was not to rank or recommend a wireless indoor environment sensor but rather to quantify the measurement errors of different sensors and to evaluate the state-of-the-art of commercially available sensors in general.

5 Conclusion

The objective of the current study was to identify and evaluate the factors that affect the CO₂ accuracy of different indoor environment sensors. The temperature, relative humidity and CO₂ concentration measurement capabilities and limitations of six wireless indoor environment sensors were quantified under tightly controlled conditions in a climate chamber.

The experimental evaluation of the CO₂ accuracy dependency did not identify a single dominant factor. The CO₂ measurement error of Sensors A, B and E was mainly affected by the CO₂ concentration. Sensor type C demonstrated higher CO₂ measurement error as the humidity level increased. Sensors D1 and D2 exhibited a strong linear relationship between temperature and CO₂ error: the measured value of CO₂ increased as temperature increased. This finding confirms the results from the study of Petersen et al. [15]. Lastly, sensor type F was affected the most by temperature and relative humidity. None of the sensors achieved the accuracies specified by the manufacturers in terms of CO₂ concentration measurements.

The temperature measurement errors of sensors A, B, D2 and C were within acceptable ranges according to EN ISO 7726 and mostly within the accuracies stated by the manufacturers.

All devices exhibited a larger error in their measurement of relative humidity than was stated by the manufacturers.

The main purpose of this study was to determine whether the measurements obtained with these sensors could be used as the input for controlling the HVAC system of a building or could be used to develop a remote commissioning process for buildings without a BMS (typically smaller buildings), or even replace the different integrated sensors of a Building Management Systems.

The results show that the selected sensors performed satisfactorily in terms of temperature measurement and could be used to control the temperature in buildings. However, this was not the case for relative humidity or CO₂ concentration measurements. Significant improvements in relative humidity and CO₂ concentration measurement capabilities are required before these types of sensors can be installed in buildings for humidity and CO₂ concentration control.

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Appendix – Additional characteristics of the chosen sensors

Table A1. Overview of some technical features of each sensor.

Sensors	Power	Age	Monitoring	CO ₂ Calibration	Internal Memory	Sampling Interval
A	Wall Plug	Used	Portal	Auto&Manual	Yes (7 days)	5 minutes
B	Wall Plug	Factory new	Portal & Phone App	Auto&Manual	No	1 minute
C	Battery (6 months)	Factory new	Portal & Phone App	Auto&Manual	Yes (3 days)	15 minutes
D1	Wall Plug	Used	Portal & Phone App	Auto&Manual	Yes (7 days)	5 minutes
D2	Battery (1 year)	Used	Portal & Phone App	Auto	Yes (7 days)	5 minutes
E	Wall Plug & Battery (5 hours)	Factory new	Phone App	Auto	Yes (3 GB capacity)	10 seconds
F	Wall Plug	Factory new	Phone App	Auto	No	1 minute

Table A2. Aggregated number of measurements for each sensor type for the respective tested temperatures.

Sensors	Sampling Interval	Test Temperatures [°C]			
		16	20	25	30
A	5 min	381	591	354	630
B	1 min	1830	2979	1653	2997
C	15 min	123	213	102	207
D1	5 min	384	603	360	654
D2	5 min	384	486	360	363
E	10 secs	11430	14466	10548	11790
F	5 min	396	492	363	378

Table A3. Aggregated number of measurements for each sensor type for the respective tested CO₂ concentrations.

Sensors	Sampling Interval	Test CO ₂ Concentrations [ppm]				
		400	800	1200	1600	1930
A	5 min	456	360	339	399	402
B	1 min	2286	1674	1599	1944	1956
C	15 min	168	114	102	126	135
D1	5 min	459	369	339	393	441
D2	5 min	342	312	297	348	294
E	10 secs	10434	9162	8892	19278	9468
F	5 min	354	318	309	294	354

Highlights

- Six different sensor types studied in a climate chamber
- Temperature, relative humidity and CO₂ concentration measured
- Factors affecting CO₂ concentration measurement errors identified
- Sensors performed satisfactorily in terms of temperature measurement
- Did not find a single dominant factor affecting the CO₂ measurement accuracy