Indoor air quality (IAQ) measurements in a tertiary building via a smart sensor connected to a Raspberry Pi card: application to a demonstrator building

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Indoor air quality (IAQ) measurements in a tertiary building via a smart sensor connected to a Raspberry Pi card: application to a demonstrator building

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Abstract. The aim of this study is to improve indoor air quality (IAQ) using an intelligent ventilation for optimal air distribution and energy consumption. For this purpose, we developed a smart multi-sensor. This device measures air pollutants (CO_2, CO,VOCs, formaldehyde, PM2.5, and benzene) and comfort parameters (temperature, humidity, noise level and lighting) in a demonstrating building. It should be noted that measurements are achieved instantly and temporally, and that data processing is done via an algorithm. This will effectively ventilate the building as needed. To go further, we conducted three sets of measurements on IAQ and hygrothermal comfort in winter, mid-season and summer in a demonstrator building room. The obtained results showed that the level of air quality is acceptable in terms of VOCs, PM2.5, formaldehyde and benzene. In addition, the CO_2 rate turned out to be high during occupancy periods. In terms of hygrothermal comfort, the air was dry and very hot, especially during the winter. This is due to the current ventilation system which does not consider the variable "humidity" to predict the comfort. Over the three measurements, we considered the occupants' perception of IAQ and hygrothermal comfort using a survey that has been proposed to occupants (students).

Keywords: Comfort parameters, Indoor air quality (IAQ), Smart ventilation.

1 Introduction

In France, indoor air quality (IAQ) in buildings has a particular attention over the past several years [1]. Since we spend 90% of our time in closed spaces (housing, office, school, transportation, etc.), the air breathed every day must be of good quality. However, many studies show that indoor air is 8 times more polluted than outdoor air. In recent years, the use of synthetic materials in building and furnishing, the adoption of new lifestyles and the intensive use of products for environmental cleaning and personal hygiene have contributed to the deterioration of quality of indoor air. As a result, they have introduced new sources of risk to humans [2]. It becomes clear that indoor air pollution has important consequences for the health of individuals. Poor indoor air quality (IAQ) can cause health problems such as respiratory system conditions (rhinitis or bronchitis), headaches, fatigue, eye irritation, nausea, etc. In

France, asthma affects 3.5 million people and severe respiratory failure affects 50,000 people. However, a good IAQ has a positive effect on the reduction of absenteeism, the well-being of occupants and their learning.

The ventilation is a well-recognized solution for reducing the variety of contaminants that can be found inside residential buildings. However, just as clean air is an essential factor for a healthy living and a healthy building, low energy consumption is significant for a healthy planet. Therefore, a good IAQ in schools is important to provide a safe, healthy, productive, and comfortable environment for occupants [3].

In France, the desire to deepen knowledge in the air quality field inside buildings has been specified in the first National Health and Environment Plan (PNSE1, 2004-2008). In addition, the issue of IAQ was the subject of the third National Health Environment Plan (PNSE 3, 2013) to study concrete actions to ensure a healthy environment.

Health and economic issues related to IAQ are important. Thereby, it is important to find a solution that improves IAQ and saves energy at the same time. The ventilation has become an important approach in the handling of the building energy consumption [4-5]. It has been stated [6] that when the ventilation flow is high in classrooms, students' performance increases by 15%. Indeed, high concentrations of CO_2 indicate that ventilation is insufficient, which can lead to health symptoms [7]. It is worth noting that a European study of 800 children in schools revealed that student scores on concentration tests decreased when CO_2 levels increased [8].

It appears that poor ventilation in schools is associated with the accumulation of indoor-generated pollutants, which is associated with “stuffy” air. Thereby, there is a high risk of infectious diseases and learning outcomes may be impaired [9]. This shows that there is a correlation between pollutants concentrations and the appearance of learners’ health disorders [10]. In school settings, IAQ has been shown to influence academic performance. Thereby, finding a compromise between the energy and health aspects is very sensitive. For this purpose, we propose a solution based on an intelligent ventilation study, which helps to preserve the health of the occupants in terms of IAQ while optimizing the rate of the air renewal. This study is based on the automation of the existing ventilation system in the demonstrator building using a smart sensor "multi-sensor sensor" that has been developed in-situ. This sensor measures several air pollutants, namely CO_2, VOCs, formaldehyde, benzene, CO, PM2.5, as well as comfort parameters (temperature, humidity, noise and brightness). The sensor has been developed via a Raspberry Pi 3-card that allows the connectivity of the case. The measurements are made instantly while allowing the building manager to know the comfort situation (thermal and sanitary) in each space of the building and act quickly in case of malfunction of the ventilation system.

2 Experimental approach description

To determine the atmospheric pollutants existing in the demonstrator building located in the Lille city, we conducted three campaigns to measure IAQ and comfort parameters. We measured the CO_2, VOCs, formaldehyde, CO, benzene, ozone and PM2.5. The comfort parameters were evaluated in terms of temperature and humidity. Previously, one of the building's rooms (T201) was instrumented. It should be noted that this room can accommodate up to 56 students (Fig. 1 and Fig. 2).

2.1. Geometry of the case study

The sensor, which measures IAQ and comfort parameters, was placed in the middle of the wall behind occupants and at a height of 1.50 m above the floor (occupants' sitting height). Usually, the sensor should be placed near the pollution source. The instrumentation room (T201) is located on the 2nd floor of the demonstrator building whose dimensions are shown in Fig. 3.

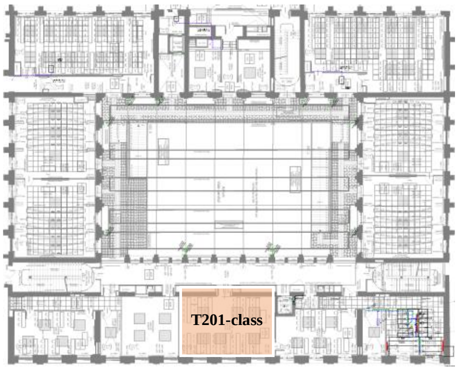

Fig. 1. The T201-class location within the demonstrator building.

Fig. 2. T201-class overview.

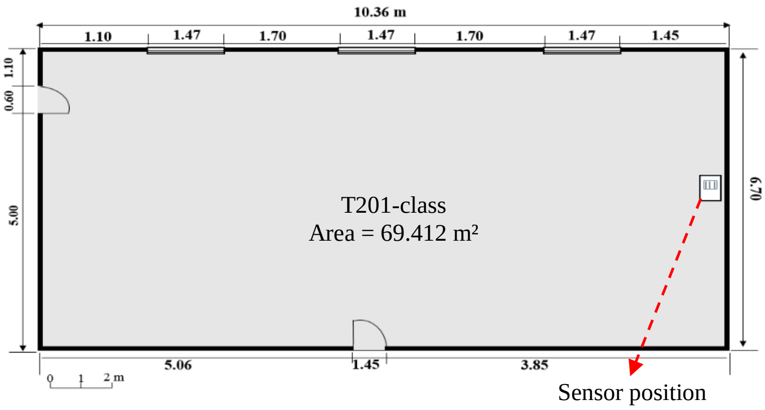

Fig. 3. T201-class dimensions and smart sensor position.

3 Results and discussion

3.1. IAQ assessment in the T201-class

In this section, we analyze the results of the three IAQ measurement campaigns and comfort parameters in the T201-class.

- **CO_2-concentrations**

During the three measurement campaigns, CO_2 levels exceed 10^3 ppm (parts per million, which is the maximum value recommended by ASHRAE 62 (Fig. 4, Fig. 5 and Fig. 6). Recall that CO_2 is produced by the human body during breathing. It is closely related to human occupation and to air renewal rates. Indeed, when the piece T201 is occupied, the CO_2 content becomes important. During holidays, its concentration does not exceed 4.10[2] ppm. Moreover, after class periods, its concentration drops to a minimum value.

It should be noted that during the first IAQ measurement period, CO_2 concentrations were high, particularly during the week of 20-24 March 2017. This is due to the large number of occupants and the insufficient ventilation rate. Note that when the CO_2 concentration is high, the air confinement becomes so high. Thereby, taking occupants into account becomes paramount as they influence IAQ through CO_2 production.

· **Relationship between CO_2-concentrations and occupation**

It is well known when breathing, we eat up oxygen and we emit carbon dioxide. A normal person emits 1kg of CO_2/day (about 20 l of CO_2 per hour). By its behavior, its uses, its living conditions and so on, the occupant plays a role as important as the technical performance of the building and systems. The CO_2 contaminant is often considered as a tracer gas allowing to know the IAQ and the confinement level. Its concentration varies according to the number of occupants, the occupation time, the ventilation rate and the space volume. It is clear that poor ventilation leads to high levels of CO_2 that will lead to a decrease in school skills. Indeed, the CO_2-concentration is proportional to the occupation (Fig. 4, Fig. 5 and Fig. 6). In addition, high CO_2-concentration indicates that ventilation is insufficient, which can lead to health symptoms.

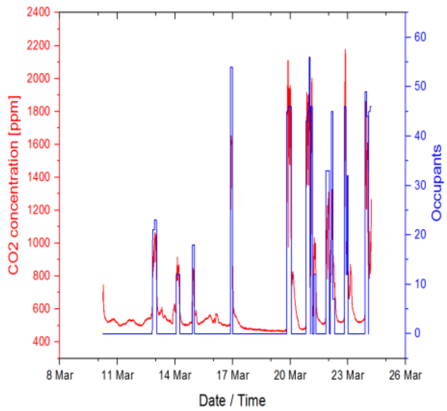

Fig. 4. CO_2-concentrations and occupancy rate during the first period of IAQ measurement.

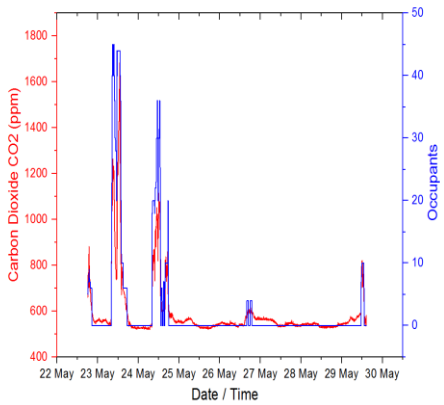

Fig. 5. CO_2-concentrations and occupancy rate during the second period of IAQ measurement.

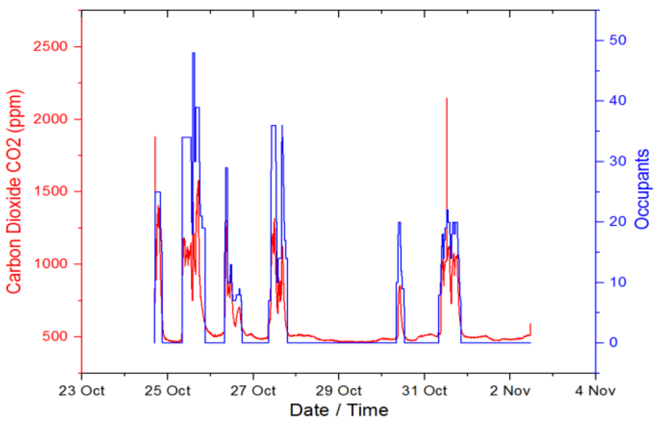

Fig. 6. CO_2-concentrations and occupancy rate during the third IAQ measurement period.
—— CO_2 concentrations (ppm) —— Occupants

· Concentrations of indoor air pollutants during measurement campaigns

Mean concentrations of volatile organic compounds (VOCs) in indoor air of T201-class and formaldehyde were found to be higher during the second period (May) (Fig. 7). This explains that VOCs are influenced by warm weather, especially when the sun is present. Fig. 9 shows that, during the month of May, indoor temperatures are higher than the first and third measurements range. This indicates that formaldehyde and VOCs levels were higher in the warm period (May).

It turns out that average particulate matter with 2.5 of diameter concentrations (PM2.5) is higher during the third period (October-November) (Fig. 7). In winter, PM2.5 concentrations in the outdoor air increase, resulting in increased values in indoor air. This may explain the high concentrations of PM2.5 during the cold period. PM2.5 from outside air seeps into homes through leaky parts (of buildings) or through windows during aeration. However, the PM2.5 concentrations inside remains very low compared to outside. Indeed, coarse particles having a diameter of 2.5 to 10 micrometers, are deposited relatively quickly on surfaces and on the ground. As a result, indoor air usually contains fewer particles than outdoor air (Fig. 8).

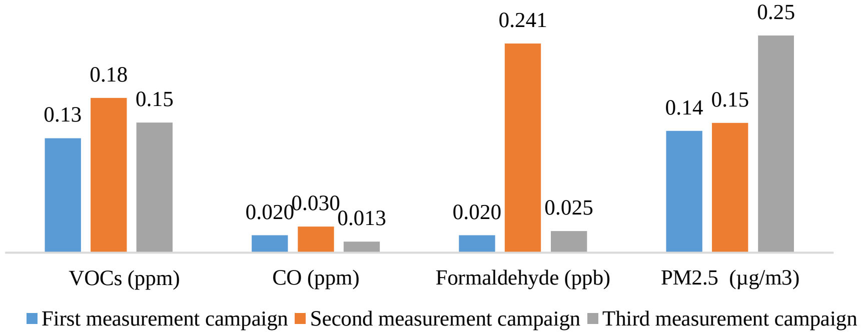

Fig. 7. Average concentrations of indoor air pollutants during IAQ measurement campaigns in T201-class.

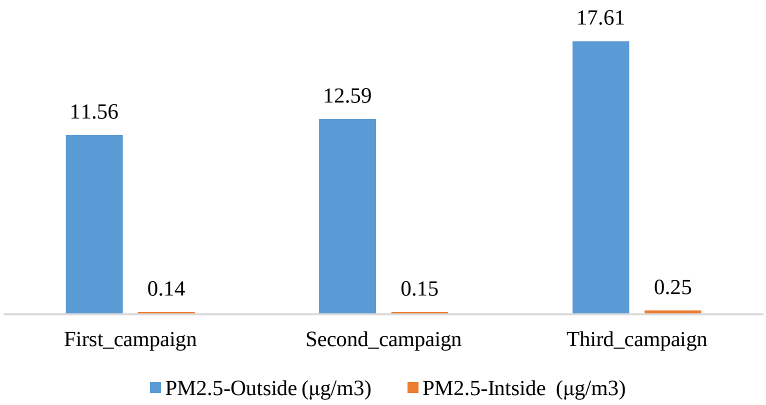

Fig. 8. Average outside and inside concentrations of PM2.5.

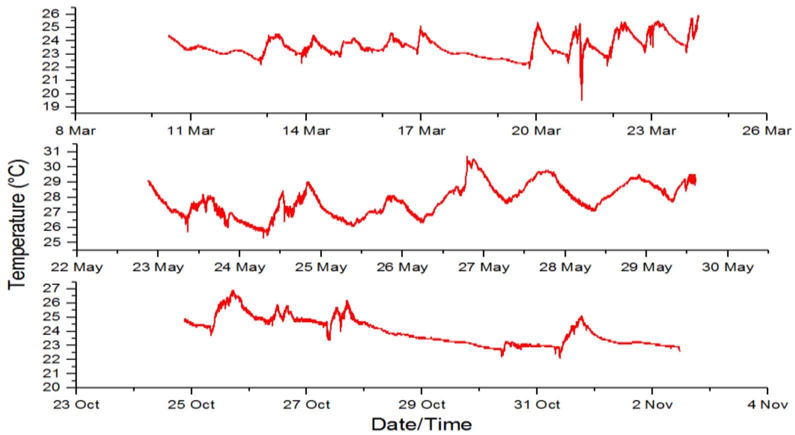

Fig. 9. Indoor temperatures during measurement campaigns.

3.2. Assessment of comfort parameters in the T201-class

· Hygrothermal comfort assessment: Humidex coefficient and bioclimatic digraph

To assess hygrothermal comfort, we involved two methods, viz. the Humidex coefficient and the bioclimatic digraph. Subsequently we conducted a survey to estimate the occupants' perception on the level of comfort felt in the T201-class. The Humidex is an index used to describe the occupants' sensation of hot or humid air. It combines temperature and humidity to reflect the perceived temperature (temperature felt). It takes both factors into account as they are decisive for summer comfort. That's why the Humidex is a better indicator of the overwhelming heat sensation than the temperature or humidity taken individually. The Humidex index was developed in Canada in 1979 by J. M. Masterton and F. A. Richardson (Eq. (1)).

Fig. 10 shows that the actual temperature and the temperature felt (Humidex) follow the same profile, while exhibiting a slight shift. Note that the indoor temperature is always higher than the temperature set at 21 °C. This means that the air in the class is very hot and not humid. Subsequently, we assessed the comfort zone using the bioclimatic diagram to locate the comfort zone of the T201-room under these conditions.

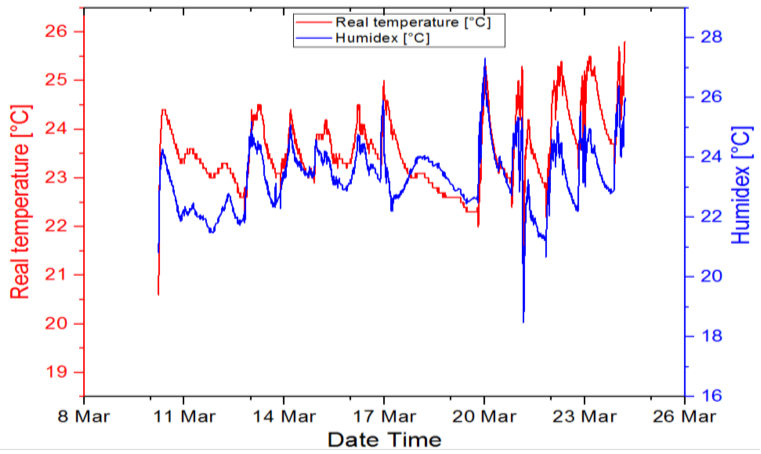

Fig. 10. Temporal evolution of Humidex index and real temperature.

$$Humidex = T_{air} + 0.5555\left(6.11e^{5417.7530\left(\frac{1}{273.16}-\frac{1}{273.15+T_{dew}}\right)} - 10\right) \quad (1)$$

where

$$T_{dew} = \left(C3\left(\ln\left(\frac{RH}{100}\right)+\frac{C2*T_{air}}{C3+T_{air}}\right)\right) / \left(C2-\ln\left(\frac{RH}{100}\right)-\frac{C2*T_{air}}{C3+T_{air}}\right) \quad (2)$$

with C2 = 17.081 and C3 = 234.175
T_{air}: air temperature (°C) and T_{dew}: dewpoint temperature (°C).

Table 1. Humidex's Range and comfort scale [11].

Humidex index	Comfort level
20 to 29	Little to no discomfort
30 to 39	Some discomfort
40 to 45	Great discomfort; avoid exertion
Above 45	Dangerous; heat stroke quite possible

Fig. 11 plots the comfort parameters (T °C and RH %) using the bioclimatic diagram and (Eqs. (3) - (4)). The ambient humidity varies between 21 and 51 % (air being dry). This explains the results obtained when calculating the Humidex coefficient to evaluate the comfort temperature. This is because the regulation of the ventilation system is based only on the temperature measurement and not the humidity temperature. In addition, it is found that the temperature is too high (24 °C) in the room during the entire measurement period (offseason). Knowing that the comfort temperature for a seated person is 21 °C, comfort is not set up in this case and hygrothermal comfort conditions are not met.

$$SH = \frac{0.622 \times p_{sat}(\theta) \times RH}{101325 - p_{sat}(\theta) \times RH} \quad (3)$$

$$p_{sat}(\theta) = \exp\left(23.3265 - \frac{3\,802.7}{\theta + 273.18} - \left(\frac{472.68}{\theta + 273.18}\right)^2\right) \quad (4)$$

where *SH*: specific humidity ($Kg_{water}/Kg_{humid\text{-}air}$), *θ:* temperature (°C), *RH*: relative humidity (%) and p_{sat} : vapor pressure (Pa).

A review of Fig. 11 shows that more than 60% of the points are located in zone 1 (drought zone) and less than 40% are located in comfort zone 4 (hygrothermal comfort polygon). The ambient humidity varies between 21 and 51% showing that the air is dry. It should be noted that the regulation of the current ventilation system is based only on the measurement of the temperature and not the temperature and the RH %, which explains why the air was dry during the month of March. In addition, our findings seem consistent with the March 2017 survey (the hygrothermal comfort zone being between 1 and 4).

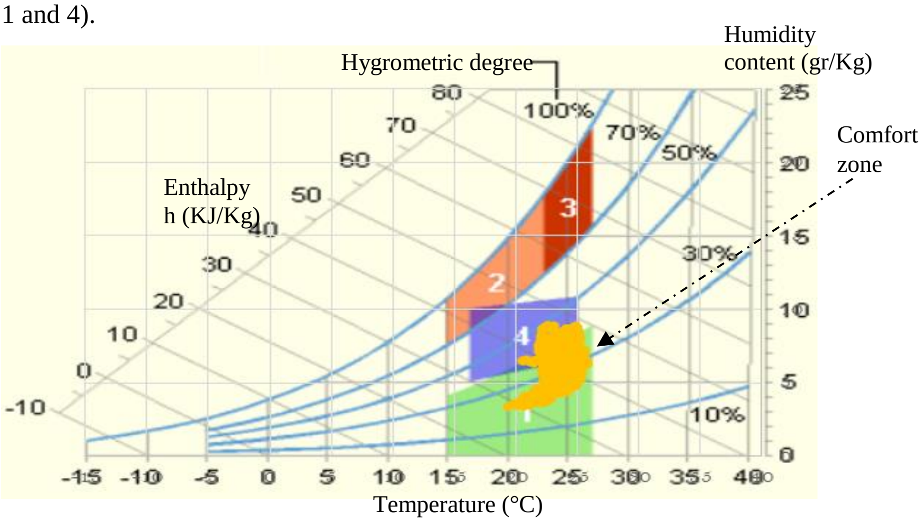

Fig. 11. Comfort zone location in the T201-class (March 2017).

In fact, the analysis of the comfort questionnaire shows that 80% of occupants were warm and the air was dry (Fig. 12). From these results, we can state that working conditions are not comfortable. This leads to absenteeism and a drop in the productivity.

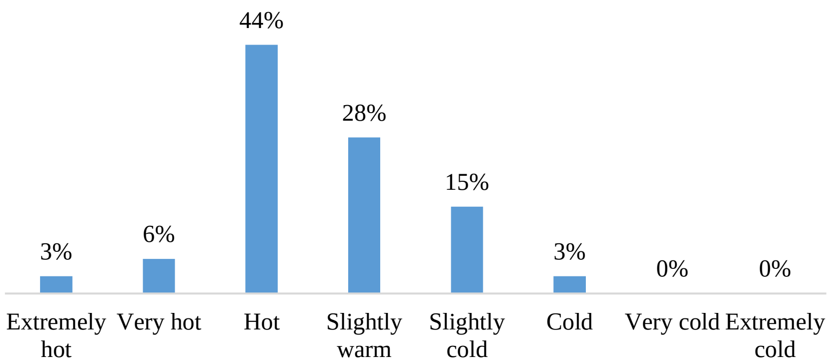

Fig. 12. Indoor temperature perception (March 2017).

3.3. The smart sensor development

The results of the three sets of IAQ measures and comfort parameters show that ventilation is not effective. In other word, the high CO_2-concentrations indicate that the ventilated airflow in the demonstrator building is not sufficient. Hence, to improve IAQ and comfort without increasing energy consumption, we proposed a solution that consists in automating the ventilation system to regulate the flow of blown air and extract it if needed via a smart sensor. The developed sensor will equip the demonstrator located in the Lille city (France) to monitor the variation of IAQ and comfort. The "smart sensor" is connected to a Raspberry Pi model 3B card whose the main purpose is to connect the smart sensor (IAQ and comfort parameters) with a ventilation system using the IoT technology (Internet of Things). Measurements are stored in a database via Wi-Fi. Fig. 13 shows the development approach of the sensor connected to the Raspberry Pi model 3B card as well as the air pollutant sensors that have been integrated. The smart sensor is in the design and improvement phase.

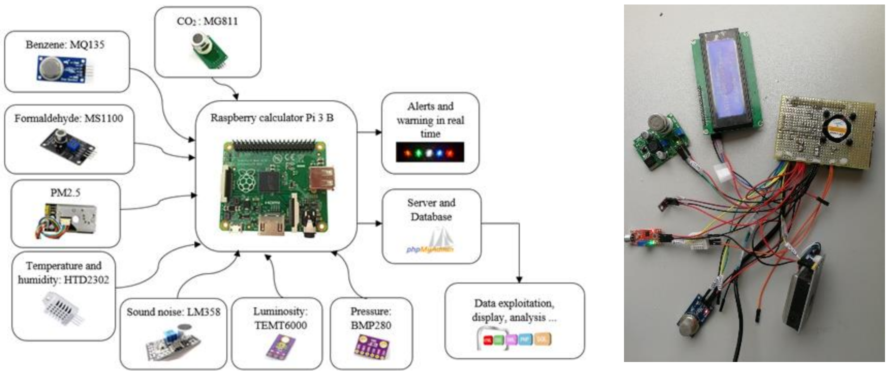

Fig. 13. Development of the smart IAQ sensor and comfort parameters (CO_2, VOCs, CO, Formaldehyde, Benzene, PM2.5, humidity, temperature, noise and brightness).

4 Conclusion

This study deals with measurements of indoor air quality (IAQ) and comfort parameters in a demonstrator building allowing to assess IAQ and hygrothermal comfort levels. The high CO_2-concentrations that have been measured in a class demonstrates the effectiveness of the ventilation system. To achieve the aim seeked, we proposed a solution based on a development of a smart sensor that measures indoor air pollutants and comfort parameters (CO_2, VOCs, CO, formaldehyde, benzene, PM2.5, humidity temperature, noise and brightness). The sensor measures atmospheric pollutants in real time and send information to the building managers in the event of malfunction of ventilation, air conditioning and heating systems.

The ultimate goal is to install the smart sensor in the demonstrator building to map the quality of indoor environments (IAQ and comfort parameters) to identify the most polluted parts. Subsequently, the ventilation system will have to regulate the flow of air blown or extracted to improve IAQ. As a result, energy consumption will be better controlled by adapting the building to the occupants' needs while improving comfort conditions to improve occupant productivity. The final goal is to improve IAQ and ensure comfort while saving energy.

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