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## MONITORING AND CONTROL OF BASIC AIR QUALITY CONDITIONS IN A UNIVERSITY EDUCATION FACILITY

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DOI: <https://doi.org/10.6036/10819> | Received: 05/ene/2023 • Reviewing: 11/ene/2023 • Accepted 20/mar/2023

To cite this article: MONTERO-GUTIÉRREZ, Paz; CERESO-NARVÁEZ, Alberto; PASTOR-FERNÁNDEZ, Andrés; OTERO-MATEO, Manuel; Pablo. QUESADA-SILVA. MONITORING AND CONTROL OF BASIC AIR QUALITY CONDITIONS IN A UNIVERSITY EDUCATION FACILITY. DYNA. DOI: <https://doi.org/10.6036/10819>

### ABSTRACT:


Carbon dioxide concentration, temperature and relative humidity in an indoor environment are some of the main indicators that determine the basic conditions of indoor air quality (IAQ). These parameters are directly related to the airborne transmission of diseases. In this context, ventilation regulation is essential to balance safety through air renewal, with comfort and energy efficiency. In this research, an educational space of the School of Engineering at the University of Cadiz is considered to monitor and control IAQ. To begin with, the weaknesses of the ventilation and air-conditioning systems are analyzed and identified. Next, a low-cost device to monitor IAQ is designed, developed and prototyped with a set of sensors and control elements. Then, the room is modeled and simulated using computational fluid dynamics (CFD), to select the location (placement/layout and quantity) of the sensors responsible for measuring the parameters that characterize IAQ. Finally, the wirelessly collected data are evaluated for interpretation, thanks to an Internet of Things (IoT) platform, in real time or deferred.

**Key Words:** Indoor air quality (IAQ), CO<sub>2</sub> concentration, CFD simulation, sensor calibration, Internet of Things (IoT)

### RESUMEN:

La concentración de dióxido de carbono, la temperatura y la humedad relativa en un recinto interior son algunos de los principales indicadores que determinan las condiciones básicas de la calidad interior del aire (IAQ). Estos parámetros están directamente relacionados con la transmisión aérea de enfermedades. En este contexto, la regulación de la ventilación es esencial para balancear la seguridad, a través de la renovación de aire, con el confort y la eficiencia energética. En esta investigación, se toma un espacio docente de la Escuela Superior de Ingeniería de la Universidad de Cádiz para monitorizar y controlar la IAQ. Para empezar, se analizan e identifican las debilidades de los sistemas de ventilación y climatización. Seguidamente, se diseña, desarrolla y prototipa un dispositivo de bajo coste para monitorizar la IAQ con un conjunto de sensores y elementos de control. Posteriormente, se modeliza el recinto y simula por medio de dinámica de fluidos computacional (CFD), para seleccionar la localización (ubicación/disposición y cantidad) de los sensores encargados de medir los parámetros que caracterizan la IAQ. Finalmente, se evalúan los datos recopilados para su interpretación, gracias a una plataforma de Internet de las Cosas (IoT), en tiempo real o diferidamente.

**Palabras Clave:** Calidad interior del aire, concentración de CO<sub>2</sub>, simulación CFD, calibración de sensores, IoT

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## 1. INTRODUCTION

Environmental pollution affects people [1], causing a variety of problems. They can range from mild fatigue or low comfort, allergy-related symptoms, lung infections and, in more extreme cases, other deadly diseases such as pneumonia in adults or lung cancer [2]. This is not only caused in industrial environments with high concentration of pollutants [3], but is present in the life of any person [4]. There are different types of chemical, physical or biological pollutants, which are found in varying concentrations, depending on the activities carried out in the environment in question. In this regard, the World Health Organization (WHO) recognizes that indoor air may be five to ten times more polluted than the surrounding outdoor air [5].


In relation to indoor air quality (IAQ) and its contamination [6] some of the parameters that are related to the health of the users are the activities carried out in the building and its interior geometric characteristics, the construction materials, the ventilation and thermal conditioning systems or the quality of the outdoor air, among others. According to the WHO, the population of cities spends between 80% and 90% of their time indoors performing their daily activities [7], with air full of pollutants, to a greater or lesser extent. This implies a high temporary exposure of people to environmental conditions that, if not controlled [8], can trigger a series of conditions. In this context, if more than 20% of occupants of a building are affected by discomfort or illness, the WHO classifies the building as a case of sick building syndrome (SBS) [9].

In general, pollutants in the air enter the body by inhalation, affecting the respiratory system and, collaterally, being absorbed by other organs or accumulating in the tissues [10]. The symptoms associated with poor IAQ [11] include headache, dizziness, nausea, fatigue, dry skin, skin rashes, eye irritation, nasal congestion and cough. In an educational setting, these are mainly manifested by a decrease in comfort, which can trigger psychological reactions such as mood swings, poor performance due to loss of attention, and difficulties in managing interpersonal relationships [12].

In educational facilities, both students and teachers spend at least one-third of their day in closed spaces, and more specifically in classrooms seating 80 people or more, uninterrupted for several hours at a time. One of the first signs of low IAQ is a reduction in comfort, or as it is often colloquially expressed "the atmosphere is getting stuffy". According to the Guide for Ventilation in Classrooms [13] the solution would be ventilation: "...refers to air renewal, i.e, replacement of potentially polluted indoor air with outdoor air...". However, this solution conflicts with thermal comfort, mainly when opening doors and windows when outdoor environmental conditions turn out to be extreme (both hot and cold). Another element that generates reluctance when ventilating is noise [14] since, in a student environment, it is normal that there is noise in the corridors and outdoors that affects the normal development of the activity. Another way to improve IAQ is to purify the air [15] with systems that eliminate suspended particles, with filtration being the simplest and most effective method to achieve this. This is not a substitute for ventilation, which is necessary to remove other contaminants (such as carbon dioxide (CO<sub>2</sub>), volatile organic compounds (VOC), etc.).

To determine the IAQ, particularly in the aftermath of the COVID-19 pandemic [16] the CO<sub>2</sub> concentration has been used as an indicator of healthy or unhealthy environments in which the air could be a transmitter of disease. To obtain the concentrations, in some countries CO<sub>2</sub> sensors were incorporated in public spaces, such as in hospitals [17] and school classrooms [18]. Studies have been conducted focusing on the analysis of low-cost devices [19] that enable monitoring of environmental conditions, primarily those related to CO<sub>2</sub> concentrations. These devices can be calibrated or cloned instruments. The instruments establish their calibration based on standards and the devices require a calibration process to provide measurements with a known level of uncertainty. In both cases, it is crucial to know the correct points for taking measurements, as their placement influences the final measurement.

In this study, a device has been designed with open programming, allowing for self-calibration. A real case study has also been conducted and analyzed using Computational Fluid Dynamics (CFD) [20], to determine the best data collection points. Ultimately, a low-cost device has been developed to monitor the IAQ of the real case studied, enabling interaction with other building systems through IoT [21] and cloud connection.

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## 2. OBJECTIVES

The research analyzes the parameters that determine the basic conditions necessary to achieve improved IAQ in university teaching spaces, focusing on a classroom at the School of Engineering of the University of Cadiz. The following points have been addressed:

- Definition of a low-cost equipment with sufficient accuracy to monitor and control the basic indoor environmental conditions of the teaching space.
- Assembly, open programming, self-calibration and comparison with reference standards of the sensors of the device to measure indoor environmental parameters of temperature, humidity and CO<sub>2</sub> in the teaching space.
- Simulation of airflow within the control volume using CFD to determine the measurement points in the teaching space.
- Remote monitoring and representation of the data obtained by the sensors of the device, using Wifi protocols for communication and the "ThingSpeak" platform to display the data.

## 3. METHODOLOGY

The methodology, as shown in Figure 1, is based on using CFD tools to determine the positioning of the CO<sub>2</sub> measurement system. Various simulations are conducted to identify and eliminate locations with no air renewal and where vortices form. The equipment is tested in a medium-sized university classroom with a capacity for 48-80 students, and different assumptions and scenarios are defined. Then, the geometry is modeled in DesignModeler, and the various boundary conditions are defined in ANSYS Discovery 2021 R2. From the analysis of the results of the performed combinations, the placement point of the device and the instrument is chosen.

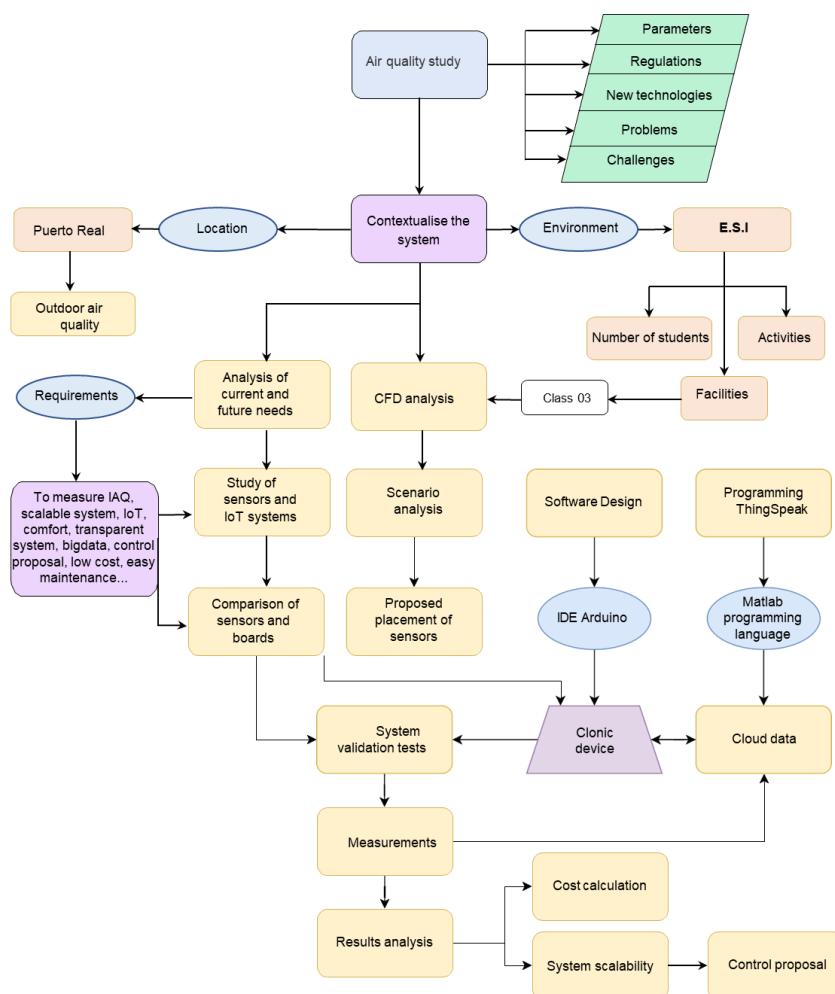



Fig. 1: Methodological scheme

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Following this, a programmable device is designed, configured, developed, self-calibrated and compared, capable of measuring, detecting, or estimating physical and chemical parameters or alterations in the environment: temperature, humidity and gases. The various elements that compose it consider factors such as IAQ, safety and health, comfort, low cost, easy installation and maintenance, open-source programming, scalability, and applicability in other spaces.

### 3.1. LOW COST DEVICE

There are four key components in the design and development of the device: a sensor to monitor the ambient temperature and humidity, two sensors to monitor atmospheric gases (CO<sub>2</sub> and smoke) and an electronic backplane to process the data. To select the most suitable components, a series of criteria on the considered characteristics are used. Table 1 shows the performed analysis:

Temperature and relative humidity sensor	Criteria	DHT-11	DHT-22	SHT-21
	Cost	6,29 €	10,39 €	7,49 €
	Temperature range: 0 - 50°C	✓	✓	✓
	Relative humidity range: 25 - 70%.	✓	✓	✓
	Resolution: < 1	✓	✓	✓
	Response time: < 5 s	✓	✓	✗
Gas and particulate measurement sensor (CO <sub>2</sub> and smoke)	Criteria	MQ-2	CCS811	MQ-135
	Cost	4,99 €	5,69 €	5,99 €
	CO <sub>2</sub> detection	✗	✓	✓
	Range of CO <sub>2</sub> concentrations : 400 - 1500 ppm	✗	✓	✗
	Smoke detection	✓	✗	✓
	Preheating condition	24 h	20 min	24 h
Microcontroller boards	Criteria	A. Nano 33 IoT	ESP 32	R.Pi Zero W
	Cost	17,00 €	8,65 €	10,44 €
	Integrated Wifi	✓	✓	✓
	Integrated Bluetooth	✓	✓	✓
	Memory	256 KB	4 MB	Requires SD
	SDRAM/RAM	32 KB SRAM	520 KB SRAM	512MB RAM
	CPU	48 MHz	2x 240MHz	1GHz
		dual-core	dual-core	single-core
	Supported programming languages	C++(arduinoide)	C++(arduinoide)	Python
		Ardublock	Esp-idf	Scratch
		C Snap4Arduino	Python	Java
		Python	RTOS's	Tiny Basic
		Tiny Basic	Micropython	C Perl
		Sketch	LUA	Ruby

Table 1. Comparison of elements for device design

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As a result of the analysis:

- The chosen sensor for temperature and humidity monitoring is the DHT-11 sensor.
- The chosen sensor for CO<sub>2</sub> monitoring is the CCS811 sensor. As an additional option, the MQ-2 sensor is included for smoke detection which adds a fire safety function.
- The chosen board is the ESP32 ESP-WROOM 32, with dual connection technology by Wi-Fi and Bluetooth, for the ease of implementation in the multiplatform Arduino IDE.

### 3.2. SELF-CALIBRATION

CO<sub>2</sub> concentration is the first and most crucial parameter for determining IAQ [22]. Additionally, knowing the temperature and humidity will subsequently help xbalance energy efficiency with IAQ by interfacing the device with the HVAC system. The CCS811 sensor is a metal-oxide-semiconductor (MOX) type. It measures total volatile organic compounds (TVOC), allowing multiple gases to be detected with high sensitivity and compatibility with CMOS integration technologies [23]. The MOX sensor combines a gas sensing element and a heating element for gas selectivity. This MOX sensor has a chemical reaction with gases (oxidation/reduction) that enables it to measure the TVOCs evaporating in the air at ambient temperature, from which it estimates the CO<sub>2</sub> concentration (eCO<sub>2</sub>).

Among the advantages of MOX sensors is their low cost [24] and low power consumption [25]. Also, assuming that the sensor is inside the building and that people are the (only) CO<sub>2</sub> producers, the correlation it establishes between TVOCs and CO<sub>2</sub> (equivalent) is significant, according to the manufacturer itself and previous investigations [26], [27] y [28]. Comparisons with other MOX sensors [29] such as the BME680 sensor, reveal its stability against transient fluctuations due to clean outdoor air currents. However, deviations are observed concerning measurements made with reference standards according to human activities, which can be mitigated by means of algorithms [30].

Regarding the calibration, self-calibration using a mathematical method can be chosen [31], such as linear functions, multiple linear or nonlinear functions (leading to linear regression processes, optimization, distributed consensus, Markov chains, Bayesian probability, maximum likelihood, etc.) or by comparison with a reference standard and subsequent re-adjustment. [32]. However, the CCS811 sensor does not require calibration, although it does need to be fine-tuned. Therefore, a break-in time of approximately one week is required, according to the manufacturer, after which it becomes stable.


### 3.3. CFD ANALYSIS

CFD simulations help to detect CO<sub>2</sub> concentration in the classroom. For this research, a simulation tool with guided workflows is used: ANSYS Discovery 2021 R2 (available at [www.ansys.com](http://www.ansys.com)). The case study analyses the atmosphere in the classroom as described above. For the proper placement of the sensors, different scenarios are analyzed, considering the following variables:

- The classroom has two front doors. One is electronically opened and the other is manually opened. Both can be in two possible states: open or closed.
- The classroom has two windows located at the back: right and left. Both can be in two possible states: open or closed.
- The classroom has a centralized air-conditioning system with individual temperature control, linked to the ventilation system, which has been in operation for eight and a half years. The air enters through the ventilation grilles, with fully open louvers, and returns through an open plenum located at the end of the classroom. The equipment can be in two states: on or off.

One way to reduce costs (be decreasing the number of points to observe) and increase effectiveness (by choosing representative points of the space) when placing the sensors is to determine where there is no air flow and where there is a continuous flow of direct air. These two situations are unfavorable for sensor placement, because a true (representative) reading of IAQ-related parameters would not be performed [32]. In stagnant air areas, the air is not renewed, becoming "stale" or polluted due to the lack of renewal. This could occur even if the classroom has the windows and doors open. The other case refers to direct flow, implying that the air is in constant movement. It can be clean external air from a window or from the air conditioning equipment.



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Using CFD, it is possible to determine the optimal position of sensors by plotting the points where there is air renewal, but without a direct flow that affects the representative measurements. For this reason, different scenarios have been considered, focusing exclusively on the dynamics of the air flow, but without considering the temperature and relative humidity factor, as this phenomenon requires a more detailed computational study. To carry out the simulations, all the elements that confine the control volume and any element likely to affect the air flow, such as the envelope and the furniture, have been modeled. The next step is the definition of the inlets and outlets of the enclosure under study (doors, windows, and air conditioning ducts), whose geometry is shown in Figure 2.

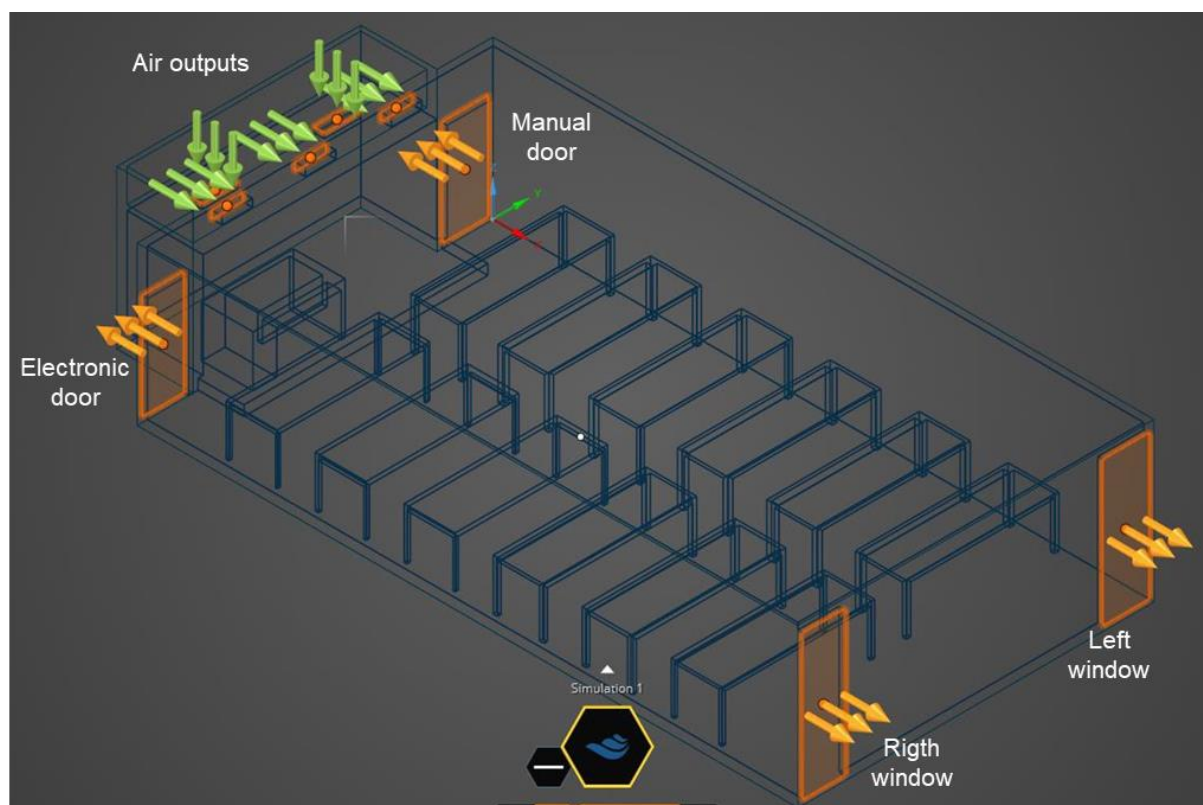



Fig. 2: University classroom under study. Characterization of air inlets and outlets

## 4. CASE STUDY

### 4.1. CFD ANALYSIS

The CFD analysis simulates a series of scenarios, with particular focus on those that involve normal operation. Among the scenarios presented in Table 2, scenarios 12, 14, 16, 18 and 20 feature cross air renewal, and the air conditioning system is in operation. This likely represents the current real situation, given the post-pandemic circumstances, where continuous ventilation and uninterrupted operation of air conditioning systems are recommended to maintain comfortable temperatures and better ventilation. In the modeling, all elements are considered to be at maximum opening when open or switched on. Figure 2 also shows the modeling of air inlets and outlets.

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Scenario	Doors		Windows		Air Conditioning
	Electronics	Manual	Right bottom	Left bottom	
1/2	Closed	Closed	Closed	Closed	Off/On
3/4	Open	Closed	Closed	Closed	Off / On
5/6	Closed	Closed	Closed	Open	Off/On
7/8	Open	Open	Closed	Closed	Off / On
9/10	Closed	Closed	Open	Open	Off / On
11/12	Open	Closed	Closed	Open	Off / On
13/14	Closed	Open	Closed	Open	Off/On
15/16	Open	Open	Open	Closed	Off/On
17/18	Closed	Open	Open	Open	Off/On
19/20	Open	Open	Open	Open	Off/On

Table 2. Scenarios simulated in ANSYS Discovery

## 4.2. CONNECTION AND PROGRAMMING

The connection of the elements, as illustrated in Figure 3, is made according to their operating voltage, the type of sensor output data, and the communication protocol with the baseboard. The MQ-2 and DHT-11 sensors are powered at 5V, while the CCS811 sensor requires a 3V supply. The Arduino IDE environment, a simple free software environment, is chosen for programming the board and its sensors.

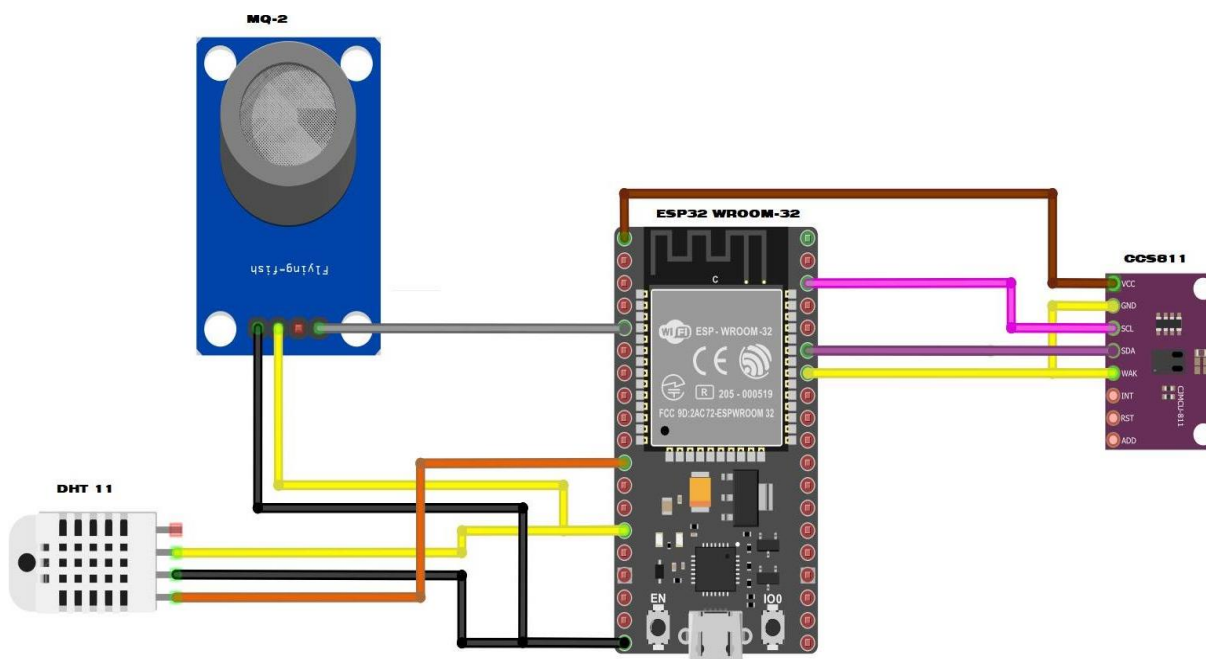



Fig. 3: Connection diagram

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### 4.3. IoT PLATFORM

Data storage is achieved through programming in ThingSpeak, which allows data updates via Wi-Fi with a very high sampling rate (<20 seconds), almost in real-time, and is accessible by all users. The schematic of the system designed to maintain thermal comfort, air quality, fire safety, light quality, and corresponding control actions is shown in Figure 4 (a). Additionally, Figure 4 (b) shows how the system can control ventilation and air conditioning by installing relays to power the control system, air conditioning flow control actuators (e.g., motorized louvers at the air outlet) and window opening control actuators (e.g., window opening motors), as well as a remote control system using a mobile application (e.g., Blynk IoT Platform). Furthermore, the system is scalable, including presence detectors (PIR), brightness sensors (LDR), light control (with dimmable and/or automatic lights) and automatic fire alarms, as shown in Figure 4 (c).

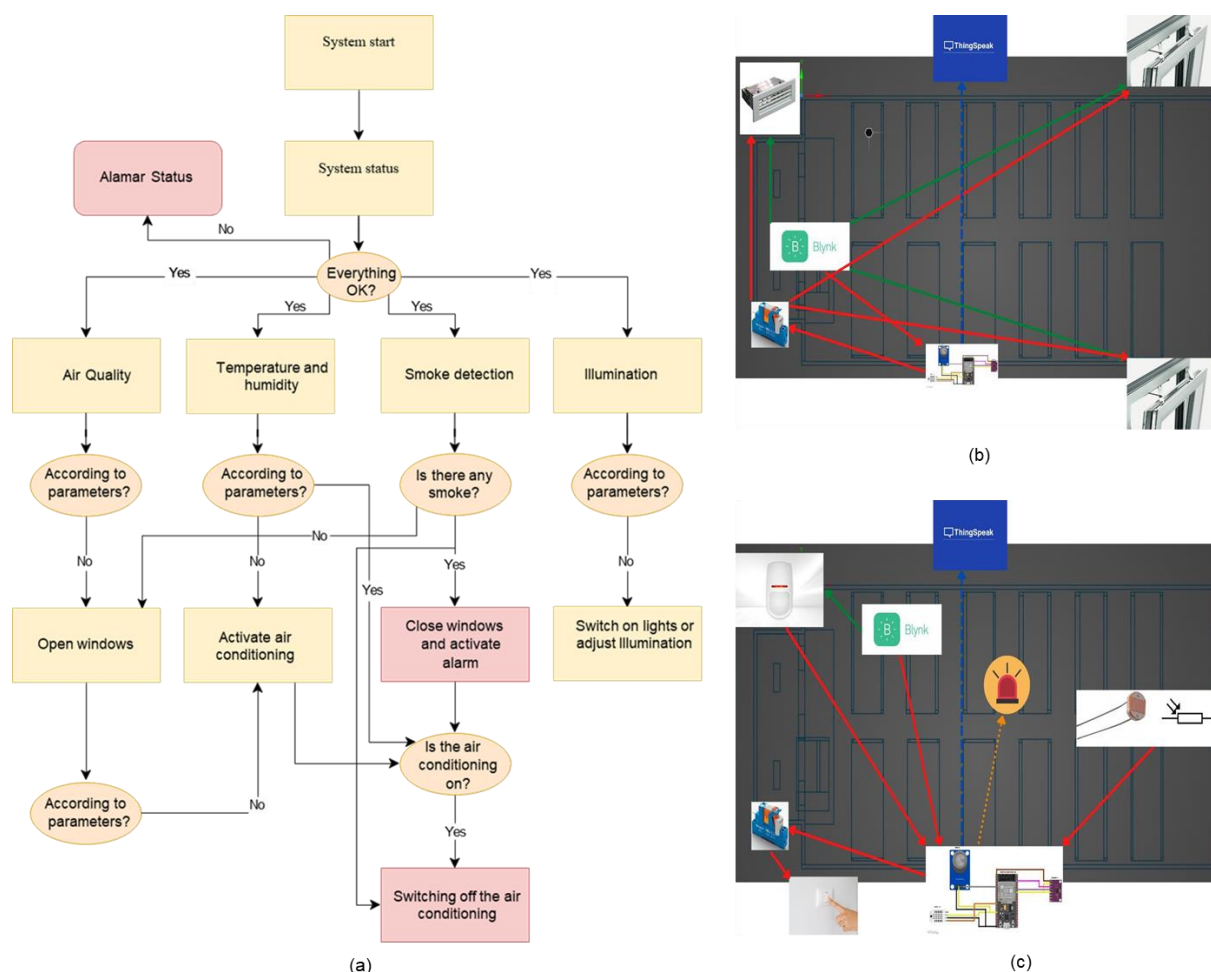



Fig. 4: Schematic: (a) Control system. ThingSpeak platform: (b) ventilation and air conditioning, (c) lighting and alarm.

## 5. RESULTS

### 5.1. FIRST PHASE: CFD SIMULATIONS

After simulating and analyzing all the scenarios, scenario 12, with cross ventilation and air conditioning on, is found to be optimal for effective ventilation of the classroom. Another aspect to consider is that both sidewalls have abrupt or stagnant flows at their ends, so the possible sensor placement area is assumed to be at a central point, away from these flow disturbances. In the classroom, checks have been carried out at the points suggested by the CFD system. This has allowed to verify that the simulation for scenario 12 offers the same critical points as indicated by the simulation and that the point selected to analyze the CO<sub>2</sub> concentration is adequate.



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In scenario 12, there is continuous air movement indoors, so the assembly should be analyzed to observe areas of possible sensor placement. The incoming flow through the window is noticeable, although this will largely depend on outside air currents and pressure differences between the inside and the outside. However, it is clear that the air flow is close to the open window and door, so it is not advisable to place sensors in their vicinity. If Figures 5-a and 5-b are observed, it can be seen that the flow from the window travels through the room to the door, but on the right wall, a continuous air flow is present, although not directly from an inlet. In contrast, in the middle area of the classroom, direct air flow is not experienced, instead constant air renewal is present and is located where the students are. Moreover, in this scenario, a single sensor of each type under the recommended ventilation conditions is sufficient to monitor the classroom.

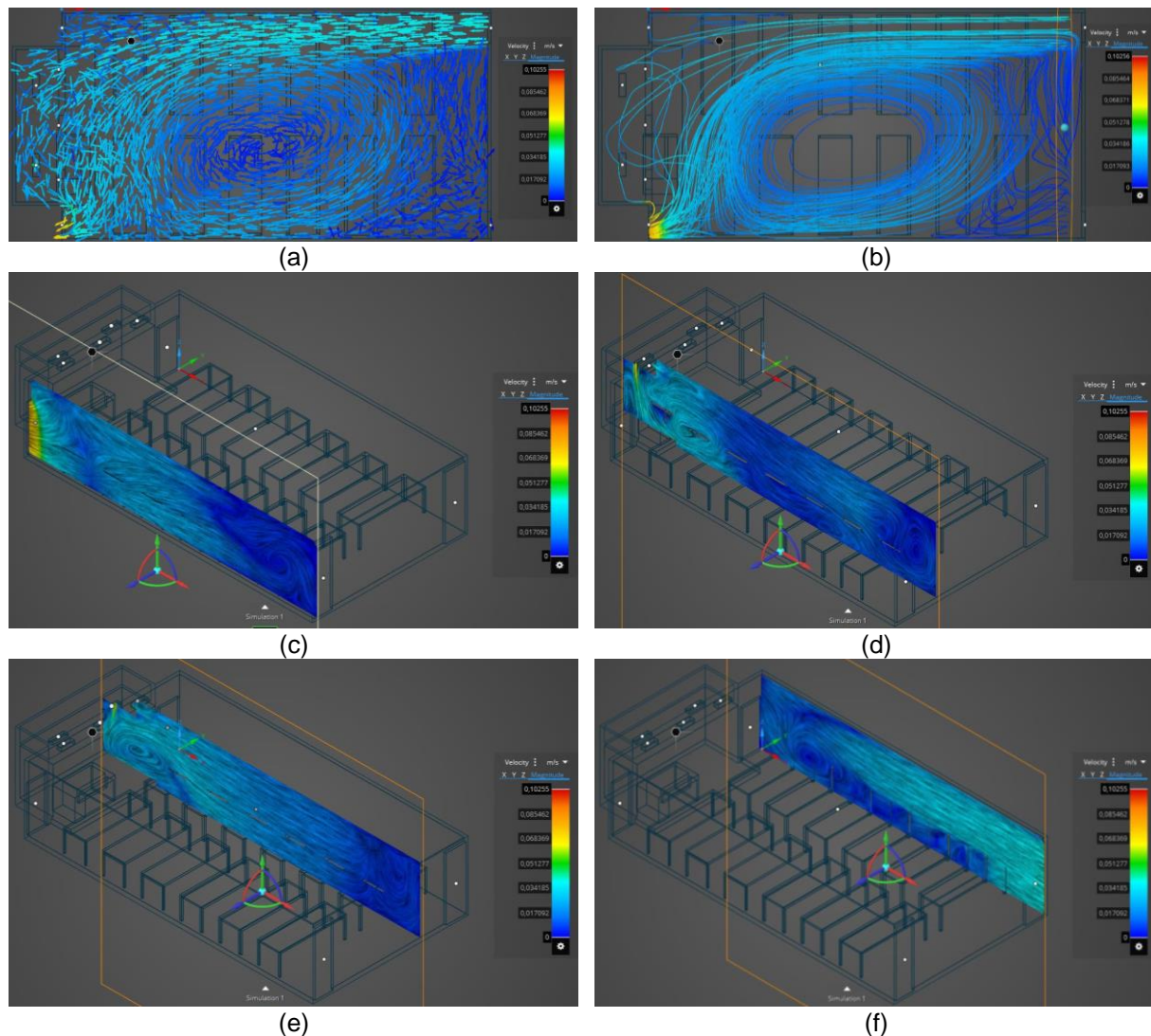



Fig. 5: CFD of the optimal scenario: (a) velocity vectors, (b) flow lines, (c-f): Shear planes, from left to right.

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## 5.2. SECOND PHASE: VALIDATION OF MEASUREMENTS

The validation of the data obtained by the sensors is performed by means of a calibrated reference standard. This device is the KIMO HQ-210P thermohygrometer, with 2 input probes: SHR 110, to measure temperature and humidity (relative and absolute), dew point, wet temperature, and enthalpy, and SCOH 112, to measure temperature, humidity and CO<sub>2</sub>. For this purpose, measurements are performed in scenario 1 with the reference standard and the equipment on a 75 cm high central table located in the center of the classroom under constant occupancy conditions. This scenario, despite not being recommended, is used, first, because it has the least currents, vortexes, and interaction with the exterior, and second, because it demonstrates its lack of suitability. Figure 6 shows the results obtained over a period of 6 hours.

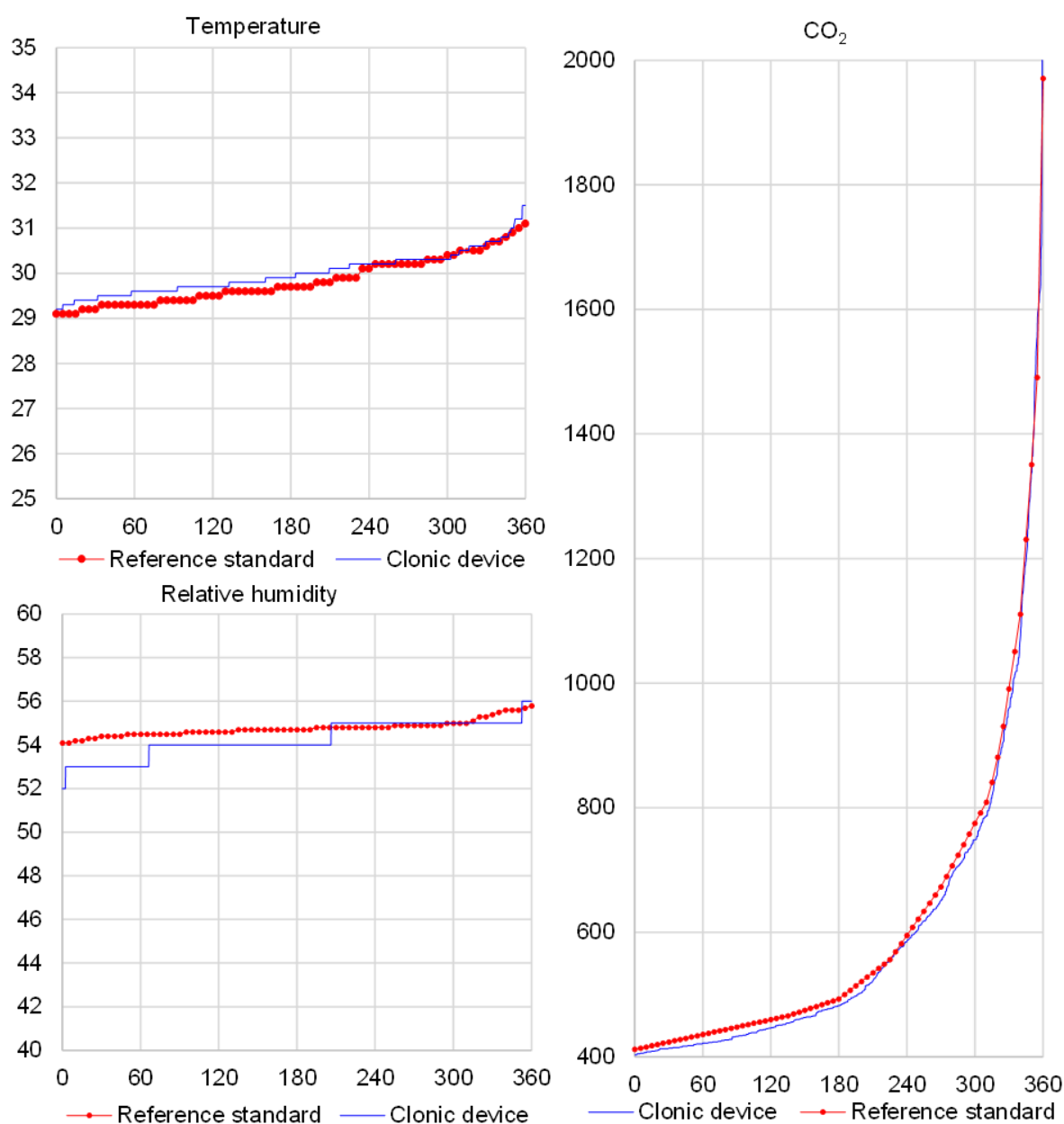



Fig. 6: Comparison of measurements: temperature (°C), relative humidity (%) and CO<sub>2</sub> (ppm) for a period of 360 min.

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### 5.3. THIRD PHASE: COST OF THE PROTOTYPE

According to the research of Villanueva et al. [33], the cheapest cost of this type of cloned devices is 75 euros. However, the proposed prototype has a lower price of approximately 60 euros, 20% cheaper, in addition to having an open-source programming language. Furthermore, the connection between the prototype and the cloud allows data collection and subsequent management, which is not possible with static devices that only provide a punctual measurement of the monitoring parameters.


## 6. CONCLUSIONS

In the COVID-19 era, CO<sub>2</sub> concentration is the most crucial indicator related to IAQ for measuring the degree of air pollution. This research addresses how to monitor and control the concentration of CO<sub>2</sub>, smoke, temperature and humidity to implement a low-cost device that helps to prevent the transmission of airborne diseases. Using commercial components, a low-cost prototype is designed, developed, assembled and programmed to measure CO<sub>2</sub> concentration. Notably, the open-source programming is easily replicable, even by end-users, eliminating the technical barriers arising from programming and the economic barriers resulting from the high price of calibrated instruments that limit their widespread use. In addition, a CFD study is conducted to choose the most suitable locations to collect data, identifying and discarding locations that may provide non-representative and unreliable measurements, due to the existence of vortices in the airflows depending on the proposed ventilation scenarios. The study allows the selection of a series of points that meet the needs for monitoring and control of CO<sub>2</sub>.

Furthermore, a methodology is proposed to help select the CO<sub>2</sub> control points based on the existing conditions in the studied indoor spaces. Also, the collected data can be evaluated on an IoT platform, in real-time or delayed. As a result, IAQ can be controlled by connecting the devices with other systems through the ThingSpeak platform. The integration of the prototype enables regulating ventilation and air conditioning, balancing safety through air conditioning with comfort and energy efficiency. This guarantees suitable conditions for the occupants while optimizing energy resources. Consequently, a smarter (and more scalable) building is achieved, which adds more value to its useful life. The main limitation is the restrictions on the reliable use of low-cost MOX-type sensors due to their high dependence on the type of human activity conducted, although educational activities are sufficiently contrasted. Future research lines should focus on analyzing aspects related to the energy sustainability of buildings, thermal comfort and its relationship with IAQ. Natural ventilation, depending on the HVAC system used, construction elements, domotic applications, and the influence of outdoor conditions, can become an essential ally in favoring the air conditioning of spaces, thus promoting overall energy efficiency.

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## ACKNOWLEDGMENTS

The authors would like to thank the PAIDI group TEP-955 (Junta de Andalucía, Spain) and the Programme for the Promotion of Research and Transfer of the University of Cadiz.