SMARTER LEARNING ENVIRONMENTS

REAL-TIME MONITORING OF CLASSROOM CONDITIONS TO FOSTER STUDENT COMFORT AND FOCUS

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Abstract

Environmental conditions in classrooms play a critical role in shaping students' health, cognitive function, and academic performance. A novel environmental data collection/analysis system was developed and deployed to take detailed samples and provide informative visuals of temperature, humidity, air quality, noise, and lighting. Perceptions of environmental factors were evaluated through outreach surveys and one-on-one interviews. Recommendations were proposed to the Universidad de Cádiz to help address deficiencies found in ambient classroom conditions and promote student well-being and learning.

Acknowledgements

We gratefully acknowledge the generous support and mentorship of Profesor Daniel Sánchez Morillo, whose expertise and guidance as project sponsor were instrumental in shaping the direction and scope of this work. Additional thanks are extended to Alejandro Lara Doña and Patricia Camacho Magriñán for their kind assistance during our time at the university, which helped facilitate our work and overall experience.

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Executive Summary

"After COVID-19, universities and educational centers began implementing air quality meters. However, many institutions still lack sustainable, accessible, and real-time solutions." - Profesor Daniel Sánchez Morillo

Our sponsor's motivation to create Smarter Learning Environments stemmed from the need to obtain indoor climate data. No existing options offered affordability, ease of implementation, and powerful analytics tools in a single package. The central objective of this project was to prototype a system capable of being useful for users ranging from scientists to facilities staff, while also not requiring an extensive technical background to operate.

In order to provide a tool useful to those it is built to serve, our project took into account the needs and perceptions of stakeholders. These were identified as students, professors, and facilities staff. Students are the main group the project was designed to assist. Not only was a survey disseminated to 77 students in order to better understand which factors were important to them, but 7 students were interviewed to qualify how they were affected personally. We interviewed 3 professors and 2 researchers to gain a broader academic perspective on how learning outcomes may be affected by classroom conditions. Finally, we spoke with 2 facilities managers, including the director of UCA campus facilities, to understand how indoor climates are currently managed. This revealed that their focus is to minimize cost over the benefit of university members.

Taking the recommendations from surveys and interviews along with the team's technical background, a system to monitor and analyze indoor environmental conditions was created. It consists of physical embedded modules placed around a room to take readings, a central server to collect and analyze data, and a web dashboard to show the resulting analysis to end users. The system was built to be modular, accessible, powerful, and simple. A data collection operation was conducted over a period of 10 days, capturing variation in classroom use across weekdays and weekends. The system was even able to restart and collect data after a nationwide blackout completely autonomously. The entire system is open source and completely free to copy/modify, with directions found in the project GitHub (7.4 Supplementary Materials).

Using the monitoring system and dashboard along with an interview outlining the negative effects of working in a room with an active soldering iron, we were able to find a clear cause of air quality degradation in the classroom. During periods of soldering use, there was a drastic increase in the presence of airborne particulate matter and volatile organic compounds whose presence signifies a decrease in air quality. Recommendations for improving air quality such as the implementation of a better fume extraction system were given to university staff to try and alleviate the issues exposed by the system and interviews.

In a seven week time frame, we were able to develop a working environmental monitoring system that was relatively low-cost, straightforward to deploy, and included a powerful data visualization framework. While it performs well in its intended role, the team has identified multiple avenues of improvement. Room capacity was cited by many as an incredibly important factor from the surveys and interviews, but was too complex to implement with the time allotted. Similarly, while sound levels were also cited as influencing engagement and learning outcomes, an interview with an acoustics researcher revealed that volume alone does not provide enough information to understand the multifaceted environmental factor. An in-depth, focused study over a long period may be able to statistically link environmental factors with health and cognitive performance. SLE proved to be not only a powerful research and monitoring tool, but a platform with significant potential for future expansion and long-term impact.

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1. Introduction

Ambient classroom environment plays a critical role in shaping students' health, cognitive function, and academic success. A growing body of research demonstrates that factors such as temperature, humidity, air quality, noise levels, and lighting conditions significantly impact concentration, memory retention, and overall well-being. Despite these effects, many educational institutions lack the necessary infrastructure to monitor environmental conditions in real time.

The Smarter Learning Environments project addressed this challenge by developing a comprehensive monitoring system that provides actionable insights into classroom conditions. Utilizing various sensor technologies, Internet of Things (IoT) integration, and Digital Twin methodologies, the system gathers, processes, and visualizes real-time environmental data to model the learning space. Surveys and interviews were conducted with students, professors, and researchers to better understand which environmental conditions to focus on, and how each condition affected their daily routines, culminating in potential recommendations for improvement.

1.1 About the Project

1.1.1 Location

The project was based at the University of Cádiz (UCA), a prominent institution in Andalusia, Spain, known for its contributions to environmental studies, marine science, and public health. Located in the coastal city of Cádiz (Figure 1), UCA faces unique challenges for indoor environments due to high humidity, salt-laden air, and fluctuating temperatures. Specifically, the Escuela Superior de Ingeniería is situated on the Campus Universitario de Puerto Real, within the Parque Natural de la Bahía de Cádiz, in the municipality of Puerto Real. This coastal environment poses unique challenges for understanding how environmental factors influence student well-being and academic performance.

Figure 1: Location of the University of Cádiz in southern Spain.

1.1.2 About the Team

The Smarter Learning Environments team brings a multidisciplinary skillset ideal for designing and innovating educational technologies that monitor classroom environment and student performance. Each major played a critical role in shaping the project. Software development and data visualizations were headed by members with computer science expertise. Electrical and computer engineering knowledge guided the integration and optimization of hardware components. Biomedical engineering contributed insights into the health implications of environmental factors, while robotics engineering enhanced automation and sensor technologies for improved data collection and analysis. Spanish-speaking team members enabled communication with local stakeholders, ensuring that research activities were contextually relevant and culturally sensitive. The complementary nature of these diverse skills strengthened the team's ability to address problems with a well-rounded perspective, utilizing technical expertise while being able to gain an understanding and be cognizant of their importance for the community.

1.1.3 Sponsor

Professor Daniel Sánchez Morillo served as the project sponsor. He works in the Department of Automation, Electronics, Computer Architecture, and Networks at UCA and leads the TIC212 Bioengineering, Automation, and Robotics research group. His work is affiliated with INiBICA, the Institute of Investigation and Innovation in Biomedical Sciences of Cadiz (Instituto de Investigación e Innovación Biomédicas de Cadiz), where his research focuses on biomedical signal processing and telemedical environments.

Throughout the project, Professor Sánchez Morillo provided consistent guidance and technical insight, particularly in the areas of system design, sensor integration and data analysis. His expertise in biomedical and environmental monitoring supported the development of a functional and research informed system. The project benefited from his feedback and commitment to promoting environmental health awareness within the university community.

1.2 Purpose

The SLE project aims to investigate the following research question:

How can a modern technology-integrated system effectively monitor classroom environmental conditions to support student well being and help improve the quality of educational spaces?

In the pursuit of this question, we developed a functional classroom monitoring system that integrated IoT technologies and Digital Twin principles to collect, analyze, and visualize real-time environmental data. While prior studies explored the impact of environmental conditions on student learning, they often lacked reproducible methods for linking quantitative environmental data to qualitative learning experiences. This project was created to help address that gap by establishing a system capable of identifying environmental shortcomings across a multitude of spaces.

The system focused on measuring variables that were identified as potential affecting classroom comfort and performance: temperature, humidity, air quality, noise, and light levels. Building on this foundation, the project provides real time data through an accessible digital platform, equipping the institution with the information needed to respond proactively to suboptimal conditions.

Beyond technical achievement, the project aims to offer benefits for multiple stakeholders. Students have easier access to healthier learning environments, while teachers can better understand how distractions stem from the environment. Facilities staff received actionable insights for infrastructure and maintenance planning. Researchers were equipped with tools for collecting data over a long period of time to inform improvements in school design and regulation.

1.3 Stakeholders

The project involves a range of stakeholders, each bringing unique perspectives and needs that shape the development and potential applications of the system. These stakeholders were organized into three groups: students, professors, and university staff.

Students served as the primary stakeholders, as the project was directly informed by their learning conditions and classroom experiences. Their feedback provided insight into how environmental factors influenced comfort and academic performance. Survey responses and interviews helped align system design with their daily needs, ensuring that environmental improvements supported both well-being and educational outcomes.

Given their direct connection to students, professors are also an important stakeholder. Their familiarity with the classroom environment and direct interaction with students positioned them to provide practical input on how environments influenced learning outcomes. In addition, their observations helped interpret how changes in physical space affected student engagement and performance.

University personnel contributed to directing the project's academic and technical development. Their input helped validate the methodology, supported data interpretation, and connected the project to broader initiatives in environmental health and educational technology. Their involvement also ensured that the system met standards and remained open for future development and use in studies or other applications.

1.4 Objectives

SLE's primary goal was to develop a scalable monitoring system capable of evaluating the impact of environmental factors on students in a classroom setting. To achieve this goal, four secondary objectives outline the project structure: identifying key environmental factors, implementing a system to collect environmental data, developing an intuitive user interface (UI) to view the data, and understanding how quantitative environmental data was linked to lived experience of students and related stakeholders.

1.4.1 Identifying Environmental Factors

The first objective was to identify environmental factors that were important to students. Research revealed factors to focus on should include temperature, humidity, air quality, room capacity, noise and light levels to determine their effects on students within classrooms. Each of these factors are perceived differently by individuals, emphasizing the need to conduct surveys that link environmental conditions to students' comfort. It is also important to note that while these and more quantitative factors have been identified, the nature of the project timeline only allowed for the implementation of a subset of factors.

1.4.2 Collect Environmental Data

The second objective was to collect environmental data around the classroom. This was done through a suite of sensors transmitting data to a microcontroller, which then sent the information to a local server for storage in a database. This process enables consistent monitoring of classroom conditions for both real time and historical contexts. The sensors monitor several key environmental factors to report the health of the classroom's atmosphere. Various sensors detect levels of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), fine particulate matter ($PM_{2.5}$), and other volatile organic compounds (VOCs) that can affect indoor air quality conditions. Other sensors measure fluctuations in temperature and humidity, microphones measure sound/noise levels, and light sensors monitor brightness. By continuously collecting and analyzing these environmental factors, the system monitored the classroom's condition and provided avenues to promote a healthier and more productive environment.

1.4.3 Data Visualization

The third objective was to present data in a clear and accessible format. A website displayed environmental data through visual elements, such as graphs and a 2D model of the classroom. Sensor readings were integrated into the model to provide a real-time, spatial understanding of classroom conditions, allowing users to interpret data intuitively. Creating this interface with accuracy, relevancy, and accessibility in mind allowed the website to be as useful as possible for all potential users.

1.4.4 Understanding Lived Experiences

The final objective was to understand how these measurable environmental factors in the classroom may affect the quality of education in order to provide a foundation for future work. Part of this consists of analyzing the intersection between environmental data and its relationship between student and stakeholder feedback. Examining trends in classroom conditions alongside survey responses would identify potential associations between physical factors and students' comfort or perceptions of the learning environment. The analysis informed recommendations for improving classrooms design and environmental quality. This takes the form of a detailed report, documented system functionality, findings, recommendations, and limitations. SLE also supports future iterations, modifications, or expansions by researchers or other institutions interested in improving learning environments. Following open-source engineering principles allowed the project to be easily accessible for modifications to different applications that can be easily implemented.

2. Background Research

2.1 Environmental Impact

A study by Ukëhaxhaj, Ramadani, Moshammer, and Zogaj (2023) highlighted the significant impact of environmental factors on student health and academic outcomes. It found that temperature and humidity influence comfort, concentration, and the spread of illnesses, while indoor air pollutants such as CO_2, VOCs, NO_2, and $PM_{2.5}$ pose serious health and cognitive risks. CO_2 levels above 1000 ppm led to drowsiness, impaired decision making, and reduced attentiveness. VOCs and NO_2, often emitted from nearby traffic or industrial sources, contributed to respiratory issues and decreased lung function. $PM_{2.5}$ was particularly harmful due to its ability to enter the lungs and bloodstream, increasing the risk of long term cardiovascular and respiratory diseases.

2.1.1 Ideal conditions

Studies recommended maintaining indoor temperatures between 20–22°C and relative humidity between 40–60% to support comfort and reduce illness transmission. Classrooms benefited from proper ventilation, which reduced pollutant accumulation and helped regulate CO_2 levels. Balanced natural and artificial lighting improved focus and prevented discomfort from excessive brightness or dim conditions. Minimizing indoor and outdoor noise was also essential, as researchers identified that high-traffic noise and interior disturbances compromised learning outcomes (Rivas et al., 2014). Seasonal adjustments to temperature and lighting further supported a stable and comfortable classroom environment.

2.1.2 Well-being

Evidence connected poor classroom environmental quality to adverse effects on student well-being. Research from the BRain dEvelopment and Air polluTion ultrafine particles in scHool childrEn (BREATHE) project in Barcelona found that schools near major roadways experienced higher levels of $PM_{2.5}$, NO_2, and black carbon, which combined with indoor CO_2 accumulation to cause stress, fatigue, and respiratory issues (Rivas et al., 2014; Wang et al., 2021). Improper lighting and unregulated temperatures contributed to headaches and unease, and excessive noise elevated stress levels. These environmental burdens increased student distress, underlining the importance of continuous monitoring and mitigation.

2.1.3 Cognitive Performance

Environmental quality has also been shown to influence key cognitive functions such as memory, concentration, and problem-solving skills. Comfortable, well-ventilated, and well-lit classrooms supported higher test scores and better student engagement (Wang et al., 2021). In contrast, exposure to pollutants and suboptimal conditions impaired reasoning, attentiveness, and auditory recall. Noise, especially from traffic, disrupted students who relied on verbal processing for learning (Rivas et al., 2014). Favorable conditions including access to daylight, living plants, and fresh air fostered creativity and motivation, underscoring the importance of a thoughtfully maintained indoor learning environment.

2.2 Research Gaps

Although numerous studies have examined how environmental conditions influence student health and academic performance, several critical research gaps remained. A common limitation across environmental monitoring studies involved the reliance on nearby public air quality monitoring stations to estimate school conditions. This approach introduced inaccuracies due to spatial variability in pollutant concentrations within school buildings. Studies by Buonanno et al. (2013), Janssen et al. (2001), and Salimi et al. (2013) demonstrated that in-situ measurements within schools provided significantly more accurate data on student exposure. Furthermore, while personal exposure monitoring offered the most precise assessment, it remained underutilized due to its logistical complexity.

Existing literature also lacked clear guidance on optimal sensor placement within classrooms. Most studies failed to explore how positioning sensors in specific locations such as on walls, ceilings, near vents, or in hallways could improve data accuracy. Capturing the variability of environmental conditions across multiple areas within and between classrooms was essential for producing reliable insights into student exposure and comfort.

No studies were found that defined threshold values for triggering system alerts or administrative actions. Without defined environmental limits, monitoring systems lacked the ability to deliver timely, meaningful alerts. Establishing such thresholds would enable immediate feedback, helping educators and staff take preventive or corrective action before environmental conditions negatively affected student well-being and performance.

2.3 Previous Works

Environmental monitoring has enough demand to have both proprietary and open-source products. While various open-source attempts have been made, a readily available solution was unable to be found to be tailored to the specific goals of the SLE. Looking at these open-source products does give valuable insight into how each project succeeded, shortcomings to be aware of, and elements that were appropriate to incorporate into SLE.

The most well documented and similar project SLE was developed by Yu Wang and a team at Massey University, called the School Indoor Air Quality Monitoring Box (SKOMOBO) (Wang et al, 2017). Based in New Zealand, the SKOMOBO team selected and tested sensors to investigate low-cost options for whose results were adequately accurate when compared to scientific equipment. The study investigated sensors measuring temperature and relative humidity, carbon dioxide, particulate matter, and motion.

Figure 2 – Complete SKOMOBO device used for environmental data collection.

Not only did the SKOMOBO team investigate the accuracy of inexpensive sensor suites, but a project retrospective detailing the shortcomings and possible solutions was published. Out of the 165 assembled units, 150 were deployed in 45 classrooms among 13 schools, with 15 faulty units that were unable to be used. Many of these faulty units were damaged in transport because of their fragility, and every unit needed some processing/maintenance before it could be used. The total cost of each unit was $295, consisting of $250 worth of parts plus another 30 minutes and an estimated $40 to $50 of labor for post processing. The SKOMOBO was not designed with modularity and future upgrades in mind, so any hardware and even software updates required a partial or full disassembly to access the internals. Contributions to the SKOMOBO code base halted in 2018, possibly because of this difficulty in maintaining the project. These shortcomings should not understate the success of SKOMOBO, however. A single working unit is no small feat, and the ability to deploy 150 units speaks to the feasibility of this project. Each unit is small, good looking, and reliable in accomplishing their task.

SKOMOBO shares enough similarities to the SLE to incorporate useful aspects, as both are environmental monitors built to be deployed in a classroom environment. Most similarities exist with respect to the hardware used in data collection. Each SKOMOBO device is self-contained and put into a classroom, where it is left running to collect samples uninterrupted over a long period of time.

Differences between SKOMOBO and SLE have to do with the core design methodology. Because SKOMOBO is built with the purpose of being a piece of research equipment, it is not able to give real-time insights. This allowed for some compromises in the implementation of SKOMOBO that could not be used by SLE. SKOMOBO was built with mass production in mind, not extensibility. As a result, the hardware design is inflexible without the ability to be easily modified, making it difficult to add new functionality. Each unit was permanently built out of acrylic with custom Printed Circuit Boards (PCB), meaning modifications would require either a complete redesign or time-intensive retrofit into the existing units, which was a struggle for the SKOMOBO team when   In addition, once SKOMOBO collects data, it simply stores it permanently for research without any way to view live data or help interested parties understand trends and their implications.

Another project similar to SLE is PiMaa, an outdoor urban environmental monitoring system created by a team at Outbox Hub in Kampala, Uganda. Like SKOMOBO, PiMaa is built for monitoring environmental factors like SO_2 (Sulfur Dioxide), O_3 (Ozone), CO, NO_2, $PM_{2.5}$ temperature, humidity, and noise levels. Each monitor was placed outdoors, to help policymakers understand the quantitative effects of urbanization.

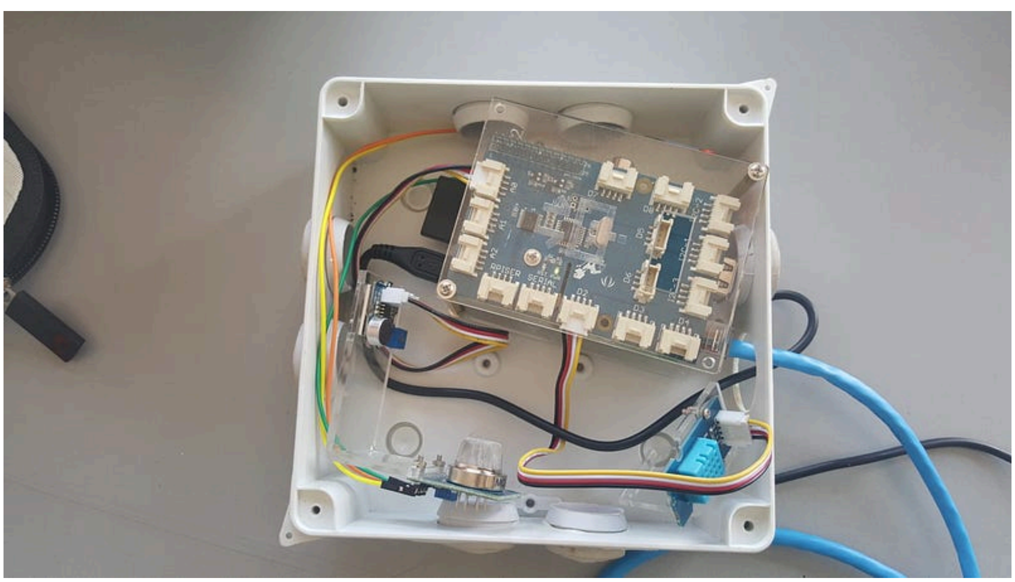


Figure 3 – Interior view of a PiMaa environmental monitoring unit, displaying its sensors and wiring.

PiMaa's architecture and deployment also helped inform the design of SLE. Each unit wirelessly communicates sensor readings to a central unit, which is IoT enabled and transcribes data into a basic spreadsheet. Instead of having one expensive unit, many cheaper ones were distributed around the city, which could help show problem areas and hotspots instead of giving summary statistics. However, design restrictions meant that readings are infrequent, with sampling taking anywhere between 10 to 30 minutes. Each unit is self-powered with a solar panel, and the wireless transmission protocol uses low-frequency radio waves which are more power efficient and much cheaper than internet access in Uganda.

One of the core design decisions of PiMaa was to be modular and able to integrate new sensors for factors like ultraviolet light and air pressure. Having a modular prototype is important for the SLE project as well, as each needs to be dynamically able to change to new focuses of public policy. Unfortunately, the project is unfinished and public contributions halted in 2018.

3. Methods

The SLE project must clearly identify key factors that shape students' experience in an environmental setting. An investigation into the perception of environmental factors in a classroom environment identified key factors that influence the students' academic performance and wellbeing. By gathering insights through observations, surveys, and discussions, we were able to understand how conditions in the physical world can impact students' sentiment towards academic performance and overall well-being. Analysis was conducted on the data collected from this research and compared with quantitative sensor data. We identified the environmental factors that were most important to the members of the university, and then examined patterns in the corresponding sensor data. This process guided research and analysis, enabling informed recommendations for optimizing educational environments.

3.1 Interview

A series of semi-structured interviews were conducted with four key stakeholder groups: students, professors, researchers, and facilities staff. Each group was selected for their unique perspectives on environmental quality, health, comfort, and performance in indoor spaces. The interview consisted of warm-up questions, open-ended prompts, and Likert-scale items tailored to their specific context and expertise. Student and professor interviews focused on classroom comfort and concentration, while interviews with medical professionals addressed the relationship between indoor air quality and respiratory health.

The questions elicited both qualitative and quantitative feedback. Open-ended prompts explored personal experiences, perceived impacts of environmental factors, and suggestions for improvement. Likert-scale items assessed the perceived importance of environmental monitoring and the desirability of access to real-time data.

Interviews were conducted in person, documented manually, and analyzed thematically. Age and gender information was collected to contextualize insights and support diverse representation across stakeholder groups. This process provided first hand insight into the everyday experiences and priorities of those directly affected by classroom environments.

3.2 Survey

To complement the stakeholder interviews and broaden the dataset, a survey was distributed among students at the university to assess how environmental factors influence comfort, focus, and productivity in classroom settings. The survey consisted of a mix of quantitative and qualitative questions, combining Likert-scale responses, rankings, and open-ended prompts to capture a comprehensive perspective. Respondents were asked to rate how comfortable they felt with specific environmental factors such as temperature, humidity, air quality, lighting, and noise, using a five-point Likert scale, where 1 indicated "very uncomfortable" and 5 indicated "very comfortable."

To understand perceived importance, participants ranked the six environmental factors from most to least critical for their classroom comfort. This forced-choice method revealed which conditions were prioritized by the majority of students when considering their well-being and performance in academic settings. Additional Likert-style questions assessed how frequently students felt distracted during class, how productive they considered themselves during lectures, and their overall sense of comfort. These questions helped establish connections between environmental discomfort and its potential impact on academic engagement.

This survey helped identify patterns in student experiences, enabling the project team to better align technical decisions with the needs and expectations of those most affected by classroom conditions.

3.3 Technical Implementation

3.3.1 Goals

A core goal of this project was to develop a functional prototype of the complete data collection and display system. From the user's perspective, this means receiving live feedback on several indoor environmental factors via a website accessible to students and faculty at UCA. This outcome was achieved through an end-to-end connection, where data flows from sensor modules to a central database and ultimately to the website.

Beyond developing a workable prototype, the modules and supporting software were built with the tenets of ease of extendibility for future contributors and ease of use for the end user. Making the implementation of the project highly customizable and flexible for a variety of applications was another central intent. This approach ensures the additional sensors or features can be integrated with minimal changes to the existing codebase or hardware layout.

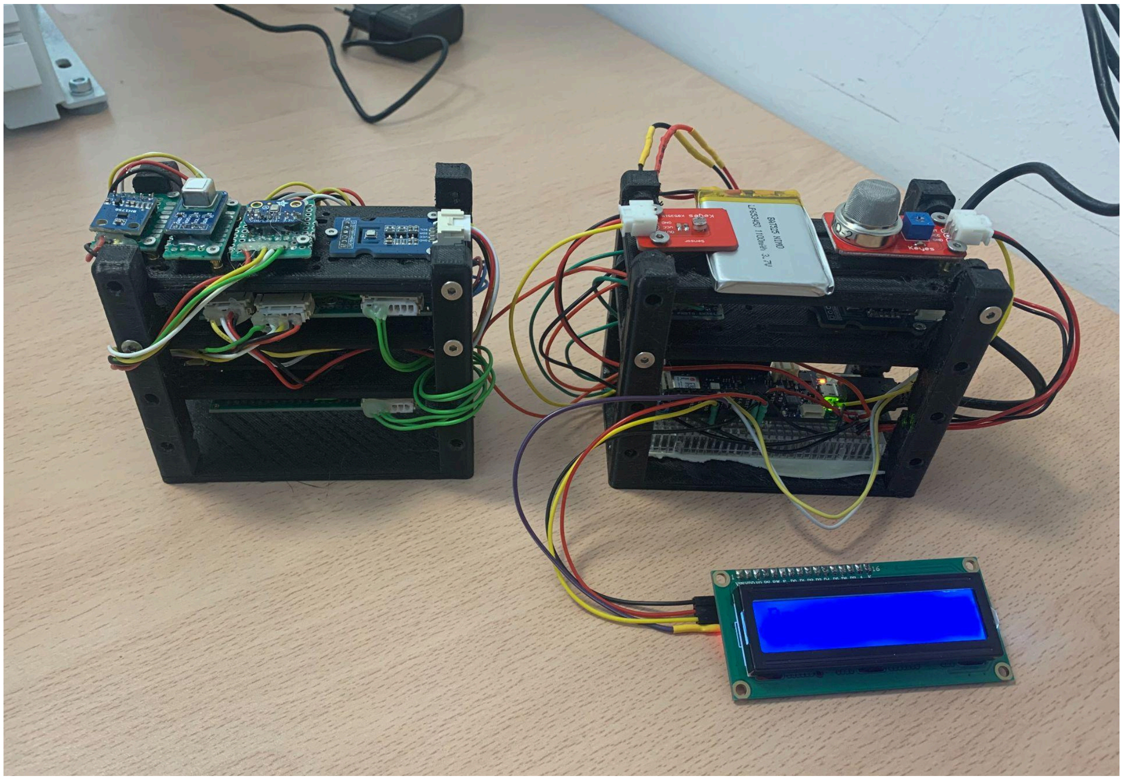


Figure 4: Sensor Modules in two configurations

3.3.2 System Architecture

By leveraging IoT technology, sensors can be integrated into a website to continuously gather environmental data for further analysis. These sensors were selected based on their functionality, cost-effectiveness, ease of deployment, and compatibility with existing systems. Collected data was transmitted to a central server for real-time monitoring and analysis. This gives an avenue for recommending potential proactive adjustments such as optimizing ventilation, regulating lighting, or controlling noise levels to create a healthier and more conducive learning environment.

Information flows through the system from the physical sensors to the client, essentially any end user. This is done by collecting data through embedded modules, using containerized services to consolidate, clean, and analyze it for trends. Finally, it is displayed to the client in a human readable and easily digestible format. The process is linear although segmented to have clear responsibility for each service, as seen in Figure 5. Embedded modules collect real time physical data through wired sensors, translate the physical sensor readings into digital packets, and send the packets over Wi-Fi to the central server. The central server listens for new readings using a message broker, and writes them to a database for long-term storage. As a client requests to see information from the front end, the back end queries the database for the necessary information, reformats it into a logical package, and returns the result to be displayed by the front end to the user.

The server-side software was containerized between four services: Database, message broker, back end, and front end. The database and message broker are both free to use, open-source software, packaged into an easily configured Docker image. The back and front end are custom solutions created specifically for SLE. Each service lives inside of a virtual Docker container in order to run on any hardware. This enabled local development regardless of the host operating system, in addition to easy deployment on any local or cloud server.

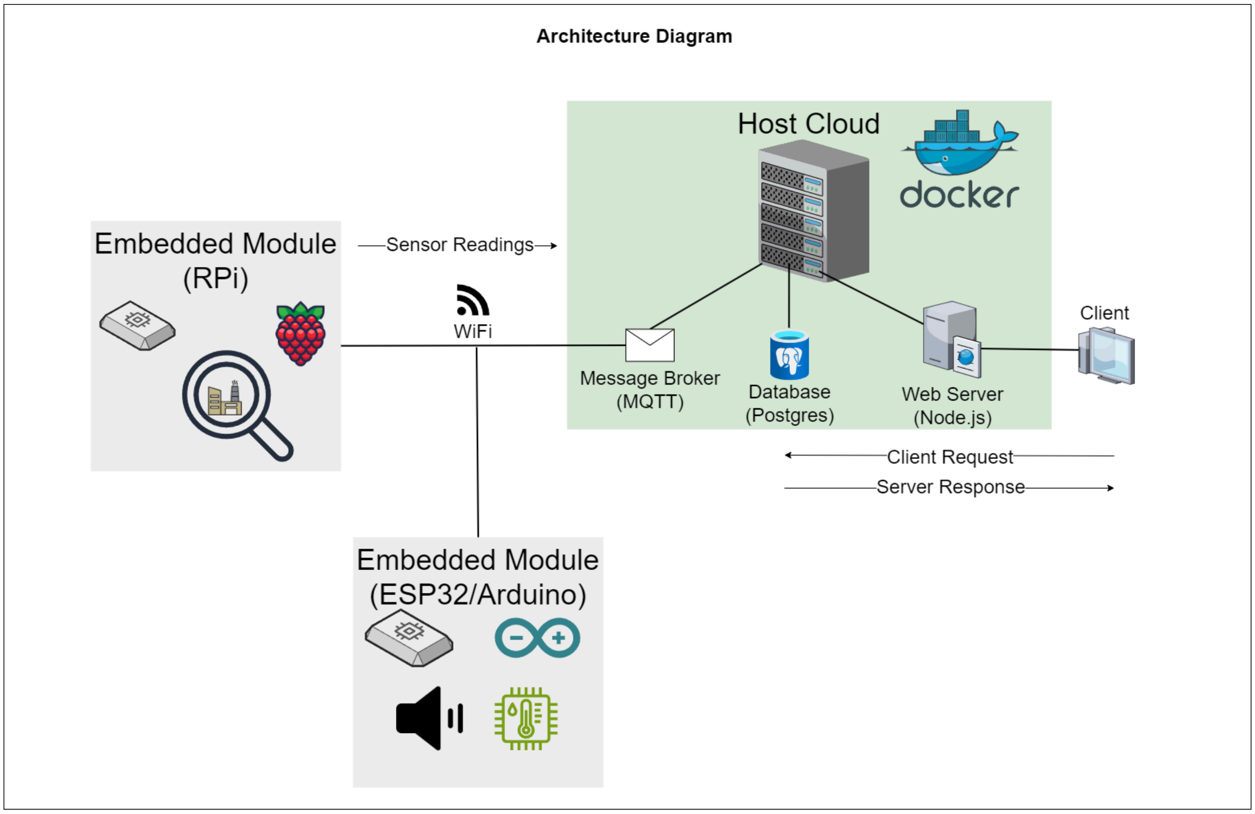


Figure 5 – System Architecture Diagram

3.3.3 Sensors

3.3.3.1 Sound

Noise levels from sources in the room would be measured using one of multiple available sensors: INMP441, SPH0645, or MAX4466. The SPH0645 is integrated inside the Enviro+ kit, while the INMP441 and MAX4466 would need to be connected directly to the microcontroller. Careful consideration must be taken to how ambient noise would be measured, with both sampling frequency and sampled metric. Further investigation of how often noise samples should be taken as well as whether to record the average noise over a period, or the loudest point in time.

3.3.3.2 Temperature, Humidity, and Air Pressure

Temperature, humidity and air pressure levels would both be measured by a single integrated sensor, the type of which would be determined by the host sensor platform. The BME680 sensor is connected to an Arduino/ESP32 while the Enviro+ board has an integrated BME280 that communicates with the Raspberry Pi. With both sensors, each module can independently collect and transmit data enabling cross-verification of the results. By comparing the readings from both sensors, this allows the confirmation of the accuracy and reliability from the data received.

3.3.3.3 Particulate Matter

The PMS5003 is a laser-based airborne particulate matter sensor. It measures the concentration of particles in the air, providing real time data through serial communication (UART/I2C). To integrate PMS5003 with the Raspberry Pi, the sensor would be connected to the UART interface of the Enviro+ board. Since the Enviro+ board is equipped with a microcontroller, the board would ensure accurate air quality readings. Similar to the PMS5003, the SPS30 shines a beam of light through an air sample to measure particulate matter. This sensor was a backup in case the PMS5003 was not delivered on time or not functioning correctly. It was not used in the final SLE prototype.

3.3.3.4 Gas

The MQ-2 is a gas sensor used to detect combustible gases such as Methane, Propane and Hydrogen. When connected to the Arduino, the sensor would react to the gases nearby by measuring a change in the internal electrical resistance. This sensor is affordable and simple to use, but needs 1-2 days to fully adjust in order to take accurate readings.

3.3.3.5 Carbon Dioxide

The SenseAir K30 is a Non-Dispersed Infrared sensor whose purpose is to accurately measure carbon dioxide levels. When connected to a Raspberry Pi through serial communication (UART), the sensor provides real time monitoring and data. However, this method would be an alternative to other choices since the sensor is not readily available to purchase.

3.3.3.6 Light

Ambient light can be measured using either the LTR-559ALS-01 or BH1750 digital light sensor. The LTR-559 has a dynamic range between 0.01-64,000 lux, while the BH1750 has a similar range from 1 to 65,000 lux, which are well within the conditions of an indoor classroom. The LTR-559 is quite cheap, has low power consumption, and comes bundled in the Enviro+ sensor package, so it can be used in both sensor-heavy or minimal module deployment options. However, the BH1750 must be integrated with a microcontroller or Raspberry Pi to transmit the data.

3.3.3.7 Room Occupancy

A PIR sensor detects motion by sensing changes in infrared radiation. The sensor would then send a signal to the Arduino if a warm object passed it, which would allow a people counter to be implemented, either through hardware or software.

The last and most complex factor to be measured was room occupancy. While no single sensor exists, integrated packages like the Terabee People Counting L-XL exist that can accurately count the flow of individuals through an entryway. While the Terabee product simplifies the data collection process hugely, it has a price tag to match and may not be easily available for others replicating the module setup. Internally, the Terabee People Counting unit uses a time-of-flight infrared sensor to detect objects moving across a threshold. An alternative to this may be to use a Pi and integrated camera + software to count people moving through an entrance, although this comes with additional development time and ethical/security risks. Another constraint the Terabee module places on the project is the need to integrate LoRaWAN capabilities to communicate with the sensor, but this would potentially allow other LoRa enabled devices to connect in the future. The high cost and integration complexity of this sensor led to it not being used in the final product, but it could be implemented in future iterations.

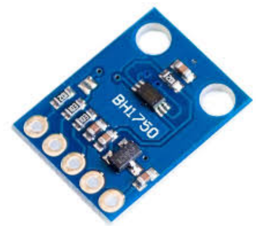
3.3.4 Hardware

To transmit the sensor data to the cloud, modules were developed to read environmental measurements and relay the information to the main processing unit of the system. Each module has an embedded microcontroller responsible for collecting specific data points from various sensors, such as temperature, humidity, air quality, light, and sound levels. Each microcontroller must have input and output pins to communicate with sensors, and a wireless communication capability over WiFi to send readings to the central server. These loose requirements allow various microcontrollers and sensor suite configurations. Three promising microcontroller families were identified for use with the project: Raspberry Pi Zero W, Arduino MKR 1010 WiFi, and ESP32 WROOM.

The Raspberry Pi Zero W is the most feature rich and powerful microcontroller of the three selected. Boasting a fully functional operating system in an ultra small form factor and pre-built sensor suites like the Enviro+, it is an easy choice as a potential microcontroller. It was used alongside the Enviro+ to collect particulate matter, air quality, temperature, humidity, and light data. This module continuously collected environmental sensor readings in real-time, storing them locally and transmitting them to a cloud-based platform.

An Arduino MKR WiFi 1010 was chosen to collect environmental data such as temperature, humidity, air pressure, noise, light and gas concentration from multiple sensors. The Arduino was powered by micro-USB. A valid alternative to the Arduino would be the ESP32-WROOM. This microcontroller was not used in the final project.

Table 1 – List of Components

Component Name and Function	Image
LTR-559 Measures ambient light and proximity to the sensor.	
BH1750 Measures ambient light intensity (lux).	
INMP441 Microphone that captures high-accuracy digital audio.	
SPH0645 Microphone that captures high-accuracy digital audio.	
MAX4466 Analog microphone with amplifier that captures analog audio signals. Was not used in the final project.	
BME680 Gas concentration sensor that has integrated temperature, air pressure, and VOC measurements.	

Enviro+ Raspberry Pi breakout board that can measure air quality, temperature, humidity, light, and noise. Has an integrated software library.	
PMS5003 PM sensor for PM_{10}, PM_5, $PM_{2.5}$, and PM_1. Used with Enviro+, and the Pi by extension.	
SPS30 PM sensor. Does not have an integrated software library, and is unused in this project.	
MQ-2 Gas sensor for liquefied petroleum gas (LPG), smoke, methane, propane, and hydrogen.	
SenseAir K30 CO_2 sensor	
PIR Sensor Detects motion based on infrared radiation changes, and by extension room occupancy. Not used in this project.	

Terabee Sensor Active people count sensors to track exact room occupancy using infrared Time-of-Flight (ToF). Expensive, but accurate. Not used in this project.	
Raspberry Pi Embedded computer that controls sensors and processes data with a full operating system. Comes with advanced features at a higher price point.	
Arduino MKR WiFi 1010 Embedded microcontroller with Wi-Fi for sensor data collection and IoT communication. Least features out of the three embedded platforms, but is cheaper than the Pi. Comes with built in support for an external Li-Po battery.	
ESP32 WROOM Microcontroller with Wi-Fi and similar functionality to Arduino MKR WiFi 1010. More configurable and cheaper than Arduino, but not used in this project.	

The electrical schematic below shows how four sensors are wired to a microcontroller with their desired pin numbers and names. The sensors that measure levels of sound, temperature, humidity and air pressure send synchronous data. However the gas concentration and light sensor transmit their information asynchronously. This means that the sensors that are synchronous require a clock signal to transmit data to the microcontroller, while the others do not.

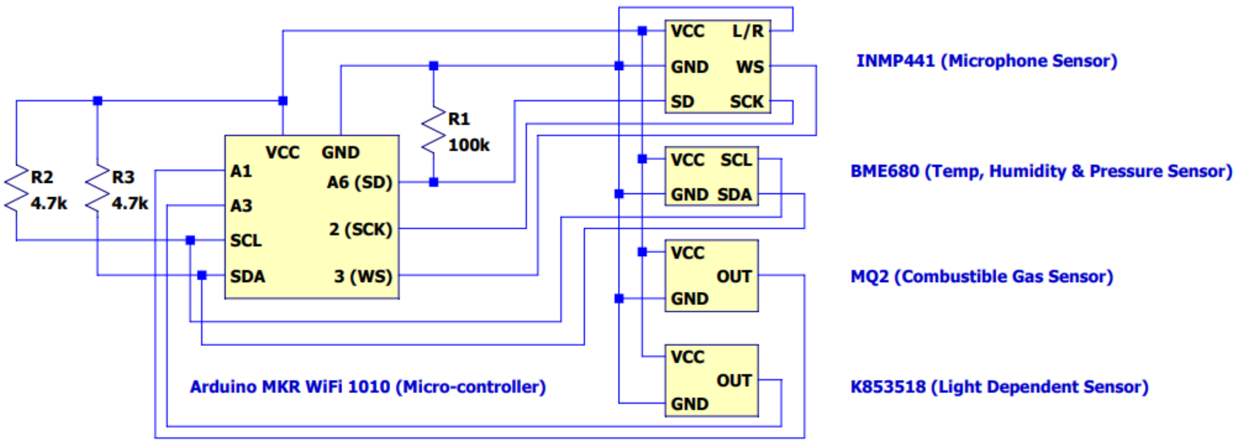


Figure 6 – Schematic of Electrical System

3.3.5 Module Housing

The SLE module housing was designed to be simple, modular, and easily modifiable. It took the form of a 3D printed open frame that supports mounting many types of hardware in different configurations. Forgoing an enclosure in favor of an open frame allows airflow to the sensors that require it, as well as keeping material usage down. Hardware can be mounted on sliding trays, so sensors can be easily added or swapped. Each tray can be printed in bulk, and can have any sensor with through holes mounted to it. Custom mounting trays can also be designed for components that call for unique mounting solutions, directionality, or other unforeseen requirements. Wires to each daughterboard from the motherboard can be easily routed around the frame. The housing for each unit takes up a small form factor of only **6.0**x**10.25**x**8.35** cm, which makes it easy to transport and unobtrusive in the classroom. The entire unit, including the outer assembly and four hardware trays, can be printed in under 10 hours with minimal post-processing and assembly.

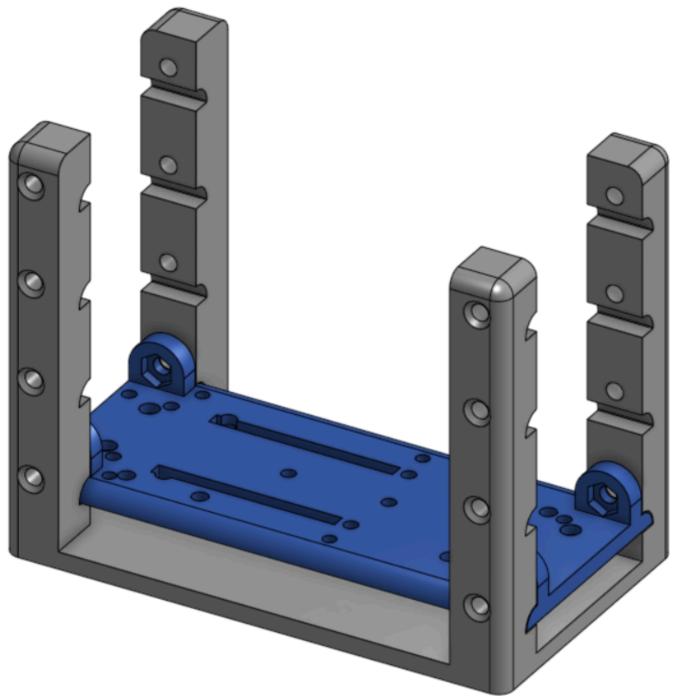


Figure 7 – Computer-aided design (CAD) model showing the housing structure for the sensors.

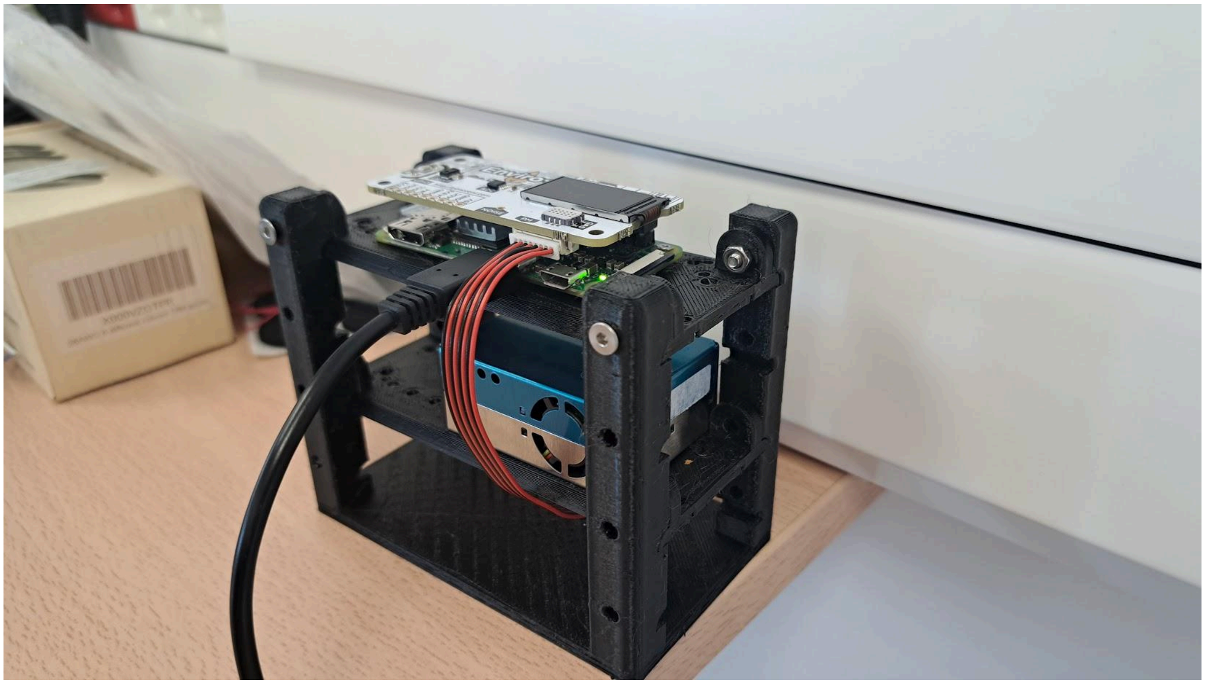


Figure 8 – Prototype model with sensors mounted on the project's custom housing design.

Figure 9 – 3D printer in the process of fabricating the sensor housing and sliding trays.

3.3.6 Software

3.3.6.1 Embedded Devices

Each physical module has an embedded device working to move data from the physical sensors to a centralized digital database. The code for these modules is built to be streamlined, robust, and easy to understand.

The first and most basic of the embedded device code is the code written for the Arduino WiFi MKR 1010. While the code is quite standard embedded C++, a notable feature is the ease of implementing new sensors. Instead of spending lots of time and effort combing through the existing code to add a new sensor, future contributors are given a simple interface where they only need to define the initialization and sensor sampling process, and all SLE-specific logic is taken care of behind the scenes.

The second and more complex of the embedded device code is for the Raspberry Pi. The code itself is mostly a modified Python template provided by the Enviro+ user guide, with extensions to communicate with the message broker. A notable feature of this device is that an operating system allows for better autonomous self-monitoring, and by extension better ability to respond to errors and faults. Defining the program as a startup service allowed the Pi to restart cleanly and collect data after a nationwide blackout without any manual intervention, showcasing the robustness of a fully-fledged and feature rich operating system.

3.3.6.2 Message Broker

The SLE message broker is the Eclipse-Mosquitto Docker image built using the lightweight MQTT protocol. In essence, the main job of the message broker is to manage real time wireless messages between devices organized in a publish-subscribe contract. . In SLE, this looks like each microcontroller publishing sensor readings over their specified topics, and the central server subscribing to each topic in order to read and store them in the database. A lightweight protocol was chosen to keep resource usage on the microcontrollers low, since the Arduino is a very resource constrained environment.

3.3.6.3 Database

For the SLE database, a PostgreSQL docker image was chosen. The database efficiently stores information sent to it, and can be used to quickly select large swaths of data that match complex criteria. This may take the form of a query for “the most recent ten-thousand abnormal sensor readings in rooms D6 through D12 during high occupancy hours”. Between the team’s background experience in SQL and Postgres’ built-in data types such as time that are an integral part of the project, it was the easiest to use out of the box and offered the best features. Usage of the database is as simple as opening a connection and sending a query, although the query itself may be complicated depending on the desired result.

3.3.6.4 Backend Service

The SLE backend service is essentially a service coupling the database, message broker, and frontend together. It is built by defining a set of Application

Programming Interfaces (APIs) that other services can call as needed to interact with the others. Each other service is self-contained with defined protocols for interaction and usage of the service, so the role of the back end is to translate and relay information between services on-demand in the background by using API calls. There are two main sets of API calls the back end takes care of: moving messages from the message broker into the database, and executing database queries for the frontend. The FastAPI Python framework (Figure 10) was chosen to define each API call, as it is simple to use while also allowing concise and custom API endpoints.

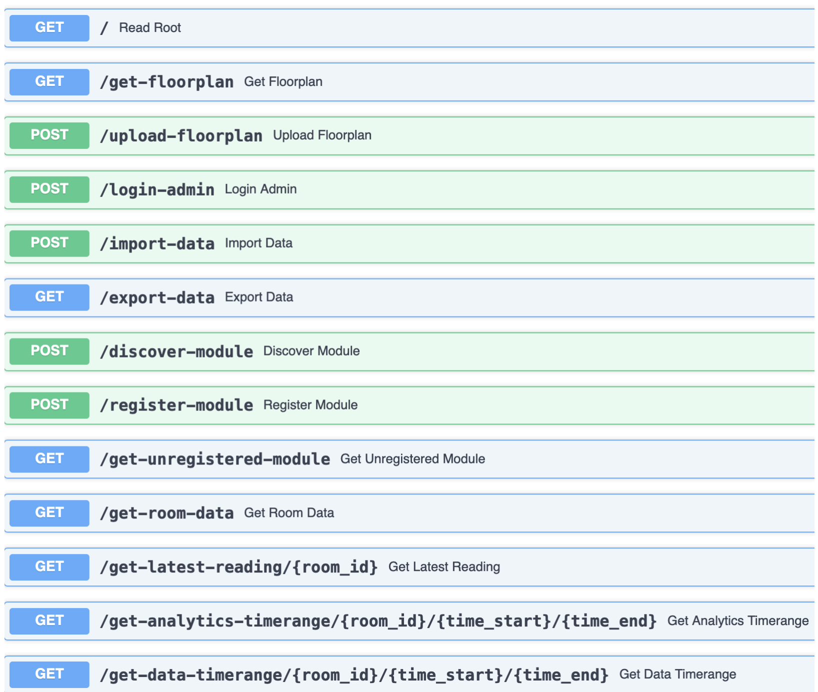


Figure 10 - A list of the FastAPI endpoints used to facilitate data transfer between services

An example of an important API endpoint used for displaying data on the frontend is /get-data-timerange (Figure 11). This endpoint takes a room ID, start time, and end time as parameters. It then returns all the readings collected in this room over the given time period, using JavaScript Object Notation (JSON) to provide structure to the output. In figure 11, an example of this JSON output is shown. Status codes are used to tell the caller of the API endpoint whether the request succeeded or failed, with 200 representing a success and 400 representing a failure.

/get-data-timerange/{room_id}/{time_start}/{time_end}

GET gets all data points in a given room from start time to end time

```
200:
{
    "time_points" :
        [
            {
                "time" : "2929289502",
                "modules" :
                    [
                        {
                            "module_id" : "0",
                            "module_xyz" : ["100", "50", "0"],
                            "readings" :
                                [
                                    {
                                        "sensor_id" : "2381",
                                        "sensor_type" : "CO2",
                                        "sensor_units" : "ppm",
                                        "value" : "600"
                                    },
                                    //...
                                ]
                        },
                    ]
            },
            //...
        ]
}

400:
{
    "error" : "invalid start time"
}
```

Figure 11 - Model used to create the /get-data-timerange API endpoint

3.3.6.5 Frontend Service

The SLE frontend service utilizes Node.js, a JavaScript runtime, in order to serve the website pages to users. The structure of these pages was built with HTML and CSS. React.js, a JavaScript library, was utilized to make the pages dynamic, allowing user interaction. This interactive setup creates a more intuitive and interesting environment, making it easy to select, read, and interpret data.

In addition to user experience, React.js has made the module registration process simpler. After the administrator sets up a new physical module, they would register the module into the dashboard. React.js provides a method for interacting with the space of an image, and thus the administrator is able to click a floor plan of the room to specify where the module is located.

3.4 User Interface

To ensure the collected environmental data is accessible and actionable for all users, a user-friendly and intuitive interface is essential. This interface takes the form of a website with a digital representation of the classroom, with tools that allow users to observe readings in the context of location and time.

3.4.1 Viewer

The most common type of user that interacts with the interface is the viewer. This user is a student or faculty at the university that wants to see the environmental data collected by the system. The viewer is not required to enter login credentials, as the website is only accessible on the university WiFi, which is already protected.

The user interface enables viewers to interact intuitively with the data to visualize trends and gain insights into the dynamics of the classroom environment. They are able to see modules in their real location on a floor plan of the room, with the latest reading from each of their sensors. This provides insight on the real-time conditions in the room. Another method users access data through is the selection of a time and date range, which shows graphs that represent all data collected over the time period. The third way users can access data is through an export button, which provides a CSV (Comma separated values) file with all information in the database. This is useful for researchers, as they would be provided with all the data in a commonly used format that is easily manipulated and analyzed.

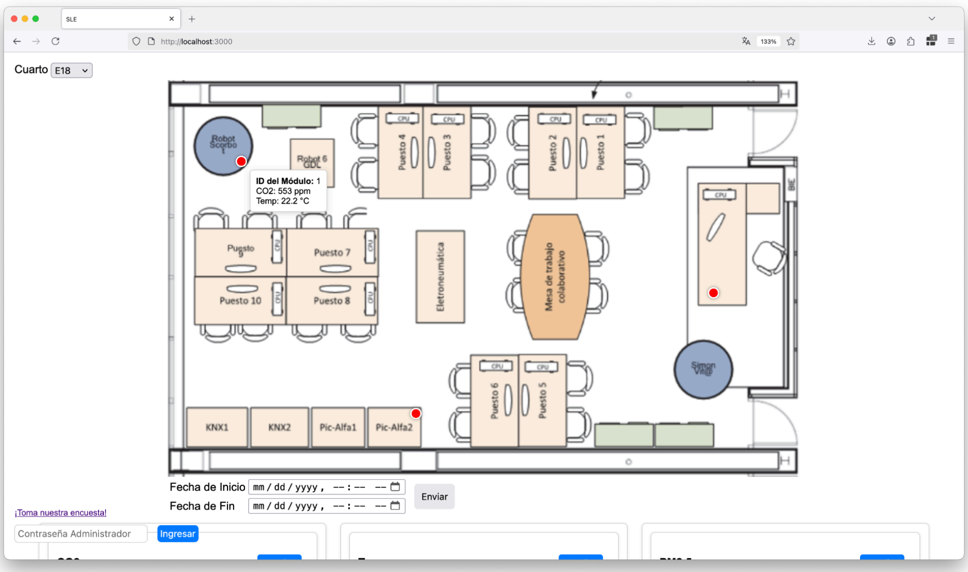


Figure 12 – User view of SLE dashboard. Most recent readings of Module 1 are shown

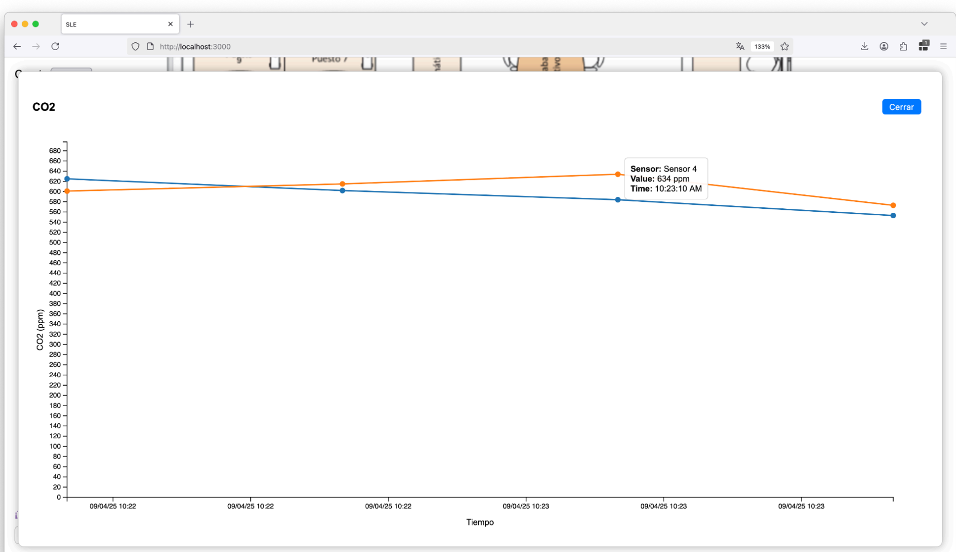


Figure 13 – Expanded view of CO_2 graph from SLE Dashboard

3.4.2 Administrator

The second type of user of the SLE system is the administrator. The administrator sets up and maintains the modules and the room on the website. In our current use case, this might be a professor at the university. Administrator credentials are required, in order to prevent viewers from editing room or sensor data.

Once they would like to set this system up in their room, the administrator would register themselves on the website. They would create a username and password, which would allow themself to log in to the website and use tools to set up the system in the room. The administrator would first be able to upload an image of their room, providing a representation for the users that would like to see the data. After an image is uploaded, the administrator is able to register “unregistered” modules. These are modules that are not currently assigned a place in a room. This registration process sets the link between a physical module and its digital representation. The dashboard is used to facilitate this setup process, providing information on unregistered modules and the ability to locate them in the room.

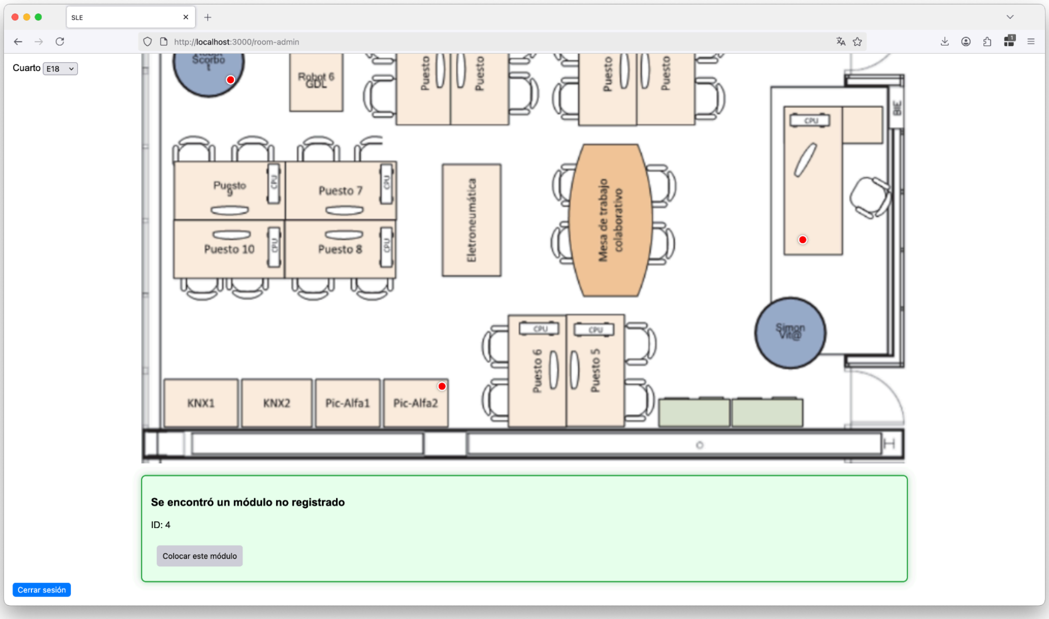


Figure 14 – Administrator view of SLE dashboard. An unregistered module that can be placed is shown.

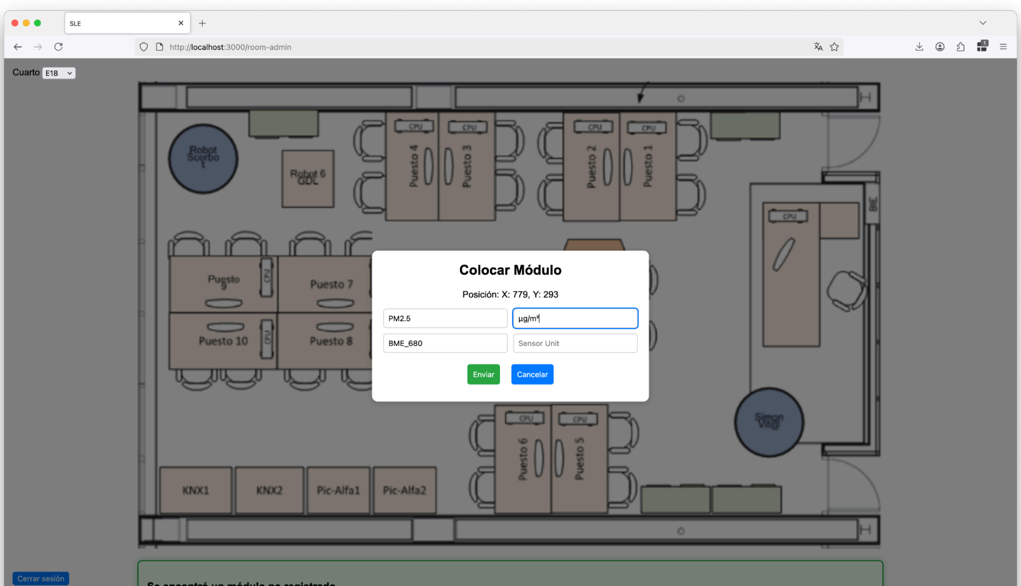


Figure 15 – Administrator view of module registration menu on SLE dashboard

4. Results

4.1 Qualitative Data

To gather comprehensive insights into how environmental conditions influence classroom comfort and academic performance, the research team conducted a series of interviews with students, professors, researchers, and university staff. These discussions provided valuable perspectives that complemented the technical data and informed the overall design and focus of the study. A total of 77 students participated in the survey, while the interviews included 7 students, 3 professors, 3 researchers, and 2 university personnel. These interviews and surveys aimed to capture both subjective experiences and objective data, providing a well-rounded understanding of the factors that impact the learning environment. This section presents the qualitative findings from the interviews and surveys, including detailed responses from students, faculty, and staff regarding the effects of temperature, noise, lighting, air quality, room occupancy, and the need for real-time environmental monitoring.

4.1.1 Student Responses

To understand how environmental conditions affected learning, the research team conducted interviews with seven engineering students across different academic years. Their responses revealed consistent patterns regarding how temperature, noise, lighting, air quality, and room occupancy influenced comfort, focus, and academic performance.

Students generally preferred cooler temperatures, citing ranges between 20°C and 23°C. Many described discomfort during both seasonal extremes like excessive heat in summer and inadequate heating in winter. Most students believed these fluctuations stemmed from the building's design, particularly the large glass panels facing the exterior as seen in Figure 16, which they said failed to regulate indoor temperatures effectively. Although the school operates air conditioning reportedly from 8:00 a.m. until 7:00 p.m., students noted that they were often unaware of the exact operating times, indoor temperatures, or whether the system functioned in real time.

Figure 16 – Glass panel exterior of the university building

Humidity also emerged as a concern, particularly among students with allergies (Student 5). While most did not actively track humidity levels, several noticed discomfort, especially during warmer months. Students attributed this in part to the school's proximity to Parque Natural de la Bahía de Cádiz and a nearby river that connects to the Atlantic Ocean, which they believed influenced local moisture levels.

Air quality was difficult for students to assess directly. While most could not define or monitor it, they noted that it felt "heavy" in crowded classrooms and during laboratory sessions involving chemicals or manufacturing tools (Student 4, Student 7). In regular lecture halls, changes in air quality went largely unnoticed unless tied to strong odors or high occupancy.

Noise levels were a recurring concern. Students consistently reported that classrooms located near the cafeteria, the outdoor open areas, or the library entrance experienced elevated noise from foot traffic and conversations. Several students described how professors left doors open to promote air circulation, but this practice allowed external noise to disrupt concentration. Sounds from neighboring rooms, dragged chairs, and mechanical ventilation systems were frequently cited distractions (Student 1, Student 6).

Lighting conditions were generally rated positively. Most students preferred a mix of natural daylight and cool-toned artificial lighting, particularly in morning classes. Several noted that poor lighting especially during early nightfall in winter negatively affected their focus and mood (Student 3).

Room occupancy also played a notable role in environmental comfort. Students explained that the more people present in a classroom, the greater the levels of body heat, noise, and stale air. Some students linked this directly to their ability to concentrate, stating that crowded rooms were overwhelming and more difficult to endure, especially during exams or long lectures (Student 2, Student 3). To further illustrate these patterns, Figure 17 presents students' responses to four Likert-scale questions addressing key environmental concerns. All participants either agreed or strongly agreed that monitoring air quality is important, that lighting and sound levels impact their classroom participation, and that they would find real-time environmental data useful. Most responses leaned toward "Strongly Agree," indicating widespread student interest in both awareness and improvement of indoor classroom conditions.

Students Responses to Likert Scale Questions

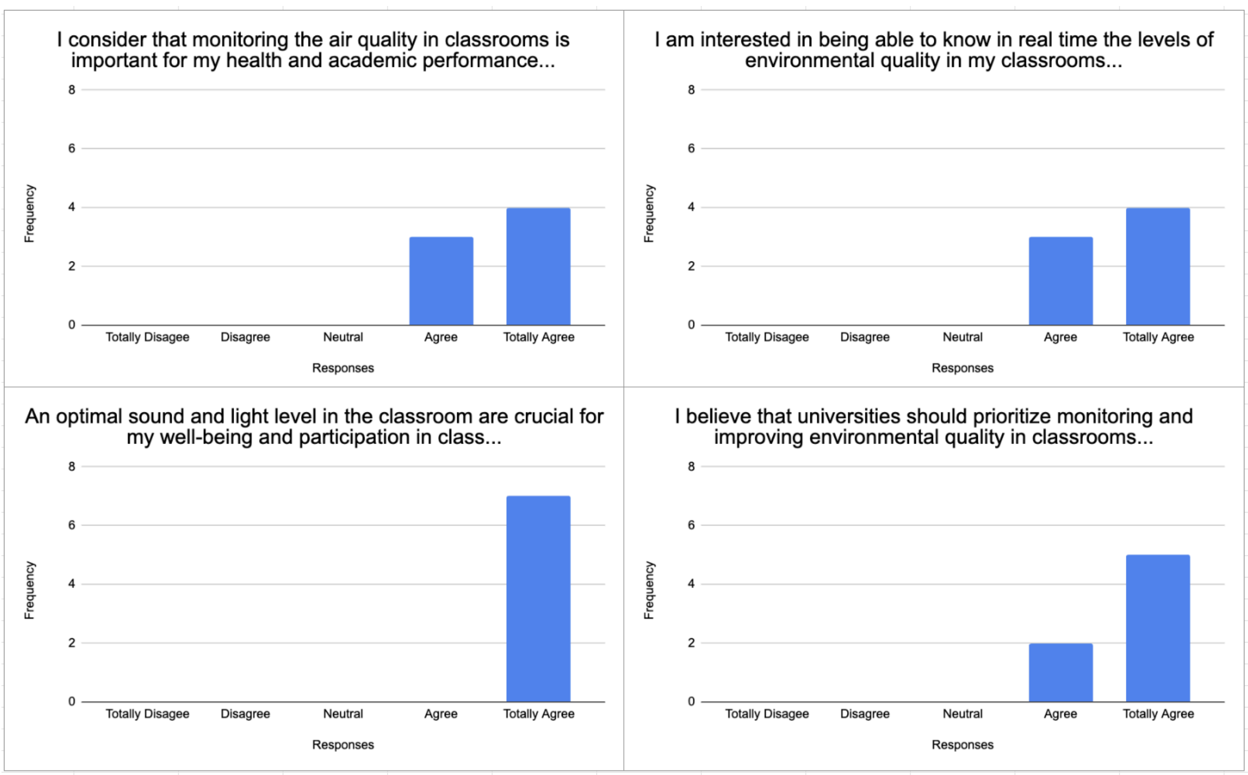


Figure 17 – Distribution of student responses to four Likert-scale questions evaluating perceptions of classroom air quality, lighting, sound conditions, real-time monitoring interest, and the importance of environmental improvements.

Following the interviews with students, a survey was conducted to gather quantitative data on how various environmental factors, such as temperature, noise, lighting, air quality, and room capacity, affected classroom comfort and student productivity. The survey responses confirmed many of the findings from the interviews, providing a clearer understanding of the broader student experience.

The survey revealed that temperature had a significant impact on students' comfort and productivity. The majority of participants rated classroom temperatures as uncomfortable, with an average score of 2.75 on a Likert scale where 1 represented "very uncomfortable" and 5 represented "very comfortable." Many students reported discomfort during both extreme heat in summer and inadequate heating during winter. This response aligns with the students’ interview comments about temperature fluctuations being linked to the building’s design, specifically the large glass panels facing the exterior that contributed to poor temperature regulation.

Humidity was another factor that influenced students' comfort, with an average score of 3.06. While students did not actively track humidity levels, many reported feeling discomfort, especially during warmer months. Students with allergies, in particular, noted how the proximity to natural parks and bodies of water could exacerbate this discomfort.

Air quality was also a concern, though it was harder for students to assess directly. The average score for air quality was 2.82, suggesting that while air quality was not always consciously monitored, students noticed it when the air felt "heavy" in crowded classrooms or labs. This aligns with interview data where students described feeling uncomfortable in environments where air circulation was inadequate.

When it came to noise levels, the survey indicated that noise was a persistent distraction, with an average rating of 3.10. Students frequently reported that classrooms located near high-traffic areas, such as cafeterias and entrances to libraries, were the noisiest. This matched the students' interviews, where they mentioned disturbances from external sources like nearby conversations and sounds from mechanical ventilation systems.

Lighting, on the other hand, received a higher average score of 3.38, indicating that most students felt comfortable with the lighting conditions in their classrooms. However, some students noted that poor lighting during winter's early nightfall negatively affected their ability to focus and engage in class activities, especially during late afternoon sessions.

Room capacity, which reflects how crowded a classroom is, showed an average score of 3.06, suggesting that while not all students found crowded classrooms overwhelmingly uncomfortable, many reported that increased room occupancy contributed to higher noise levels, more body heat, and a less productive environment. Several students mentioned that they found it more difficult to concentrate during crowded classes, particularly during exams or long lectures.

The survey results revealed valuable insights into the average comfort levels and the importance students placed on different environmental factors. The average comfort score for various factors was calculated, with lighting receiving the highest score of 3.38, indicating that most students found the lighting conditions comfortable. On the other hand, temperature had the lowest average score of 2.75, highlighting significant discomfort among students, especially during temperature extremes. These findings emphasize the need for better temperature control in classrooms to improve students' learning environments.

Similarly, the average importance of each factor was assessed, with temperature and air quality being regarded as the most important environmental conditions, reflecting their significant impact on students' comfort and productivity in the classroom. The average importance scores provided a clear view of the factors that most students felt should be prioritized for improvement. Where 1 is the most important factor and 5 is the least important factor.

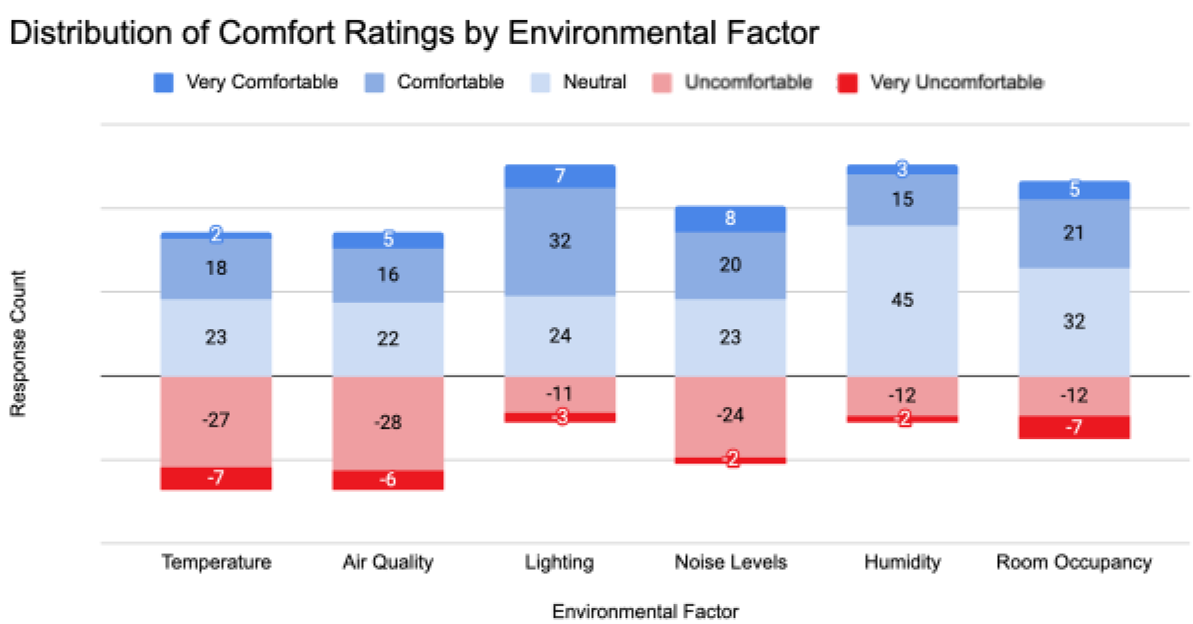


Figure 18 – Distribution of comfort ratings for Classroom Environmental Factors

Factor vs Responses	Very Uncomfortable	Uncomfortable	Neutral	Comfortable	Very Comfortable
Temperature	7	27	23	18	2
Air Quality	6	28	22	16	5
Lighting	3	11	24	32	7
Noise Levels	2	24	23	20	8
Humidity	2	12	45	15	3

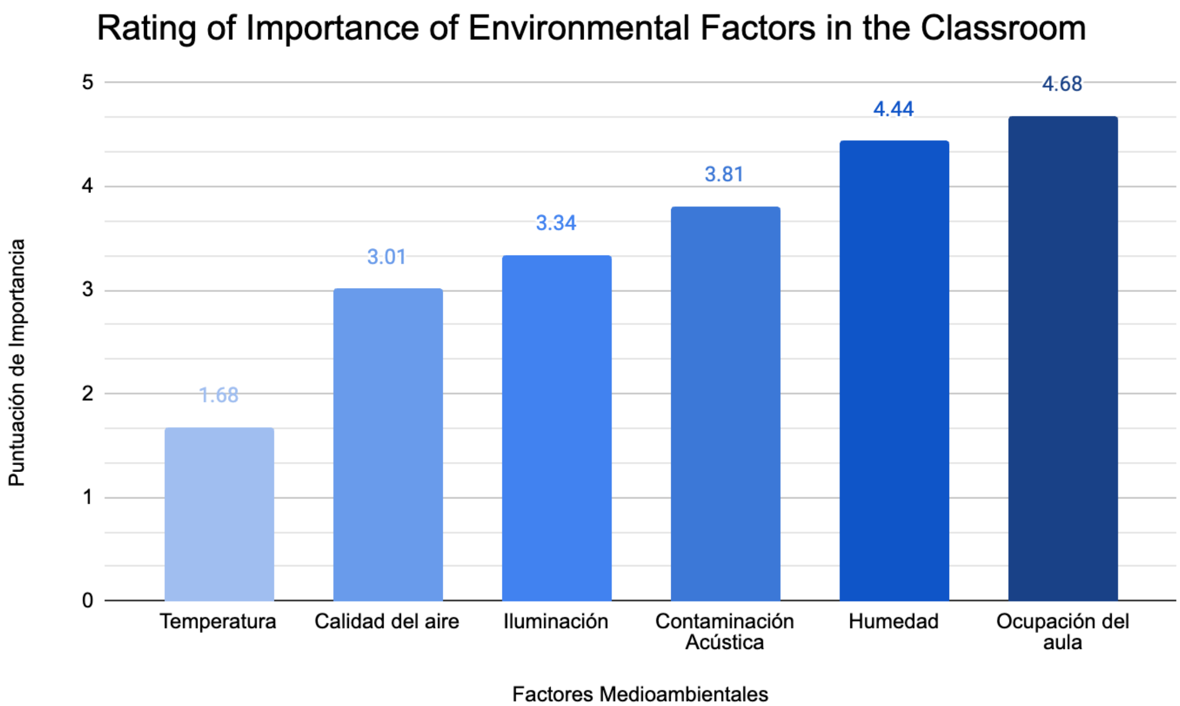


Figure 19 – Average Importance Scores for Classroom Environmental Factors

Additionally, the survey included questions about how easily students get distracted and how productive they feel during class. The responses to the question "Do you get distracted easily or hardly?" revealed that a significant portion of students reported being easily distracted, which could be linked to environmental factors such as noise levels and room capacity. Similarly, the productivity question indicated that many students felt their ability to focus was compromised, which was consistent with the concerns expressed about environmental distractions during the interviews.

To further illustrate these patterns, Figures 18 and 19 present the distribution of student responses to several key questions regarding environmental comfort and the importance of real-time monitoring in classrooms. The results from both the survey and the interviews indicate a clear demand for improvements in classroom conditions, with students showing particular interest in better temperature regulation, air quality monitoring, and noise control. Additionally, the individual responses to the survey questions, including the ratings for comfort and importance of environmental factors, are provided in the appendix for further reference.

4.1.2 Professor Responses

To complement the student interviews, the research team also interviewed three professors from different engineering departments to explore how environmental conditions influence classroom dynamics, student learning, and instructional practices.

Across the interviews, professors consistently acknowledged that temperature, air quality, noise, and lighting can impact the classroom experience, although their views varied regarding the extent to which these factors affect teaching outcomes. Professor 1, with over 40 years of experience in acoustic engineering, emphasized that environmental conditions such as noise and temperature primarily influence student comfort rather than the learning outcomes themselves. He argued that “the student's interest and motivation” remain the dominant factors for academic performance.

Nonetheless, he noted that cold classrooms in winter, when windows are left open for ventilation, severely reduce students' ability to concentrate.

Professor 2, specializing in thermodynamics and heat transfer, highlighted that temperature and ventilation were critical environmental concerns. She reported that poorly air-conditioned classrooms made it harder for students to concentrate and suggested that comfort ranges should maintain temperatures between 22°C and 27°C with good air circulation. She also observed that environmental discomfort, especially due to temperature extremes, reduced student engagement and could subtly influence academic performance.

Professor 3, who teaches automatic control systems, also stressed that poor classroom conditions directly diminished student focus and performance. He described challenges with large classroom groups, where crowded environments led to increased heat, humidity, and background noise. He estimated optimal classroom conditions `should include temperatures between 20°C and 22°C, humidity below 80%, and noise levels lower than 55 dB. He also noted that occasional hallway noise and heavy student traffic disrupted concentration during sessions.

Although perspectives differed slightly, all three professors agreed that extreme temperatures, poor ventilation, and high noise levels made classrooms less conducive to learning. However, the degree of perceived impact varied: while Professor 1 believed environmental conditions were secondary to student effort, Professors 2 and 3 emphasized a direct connection between comfort and concentration.

The Likert-scale responses (Figure 20) further reflected this split. Professors 2 and 3 strongly agreed that monitoring air quality and maintaining optimal lighting and sound were crucial for health, well-being, and academic performance. In contrast, Professor 1 showed more neutral or selective agreement, supporting air quality monitoring only in specialized environments such as mechanical workshops or chemical laboratories.

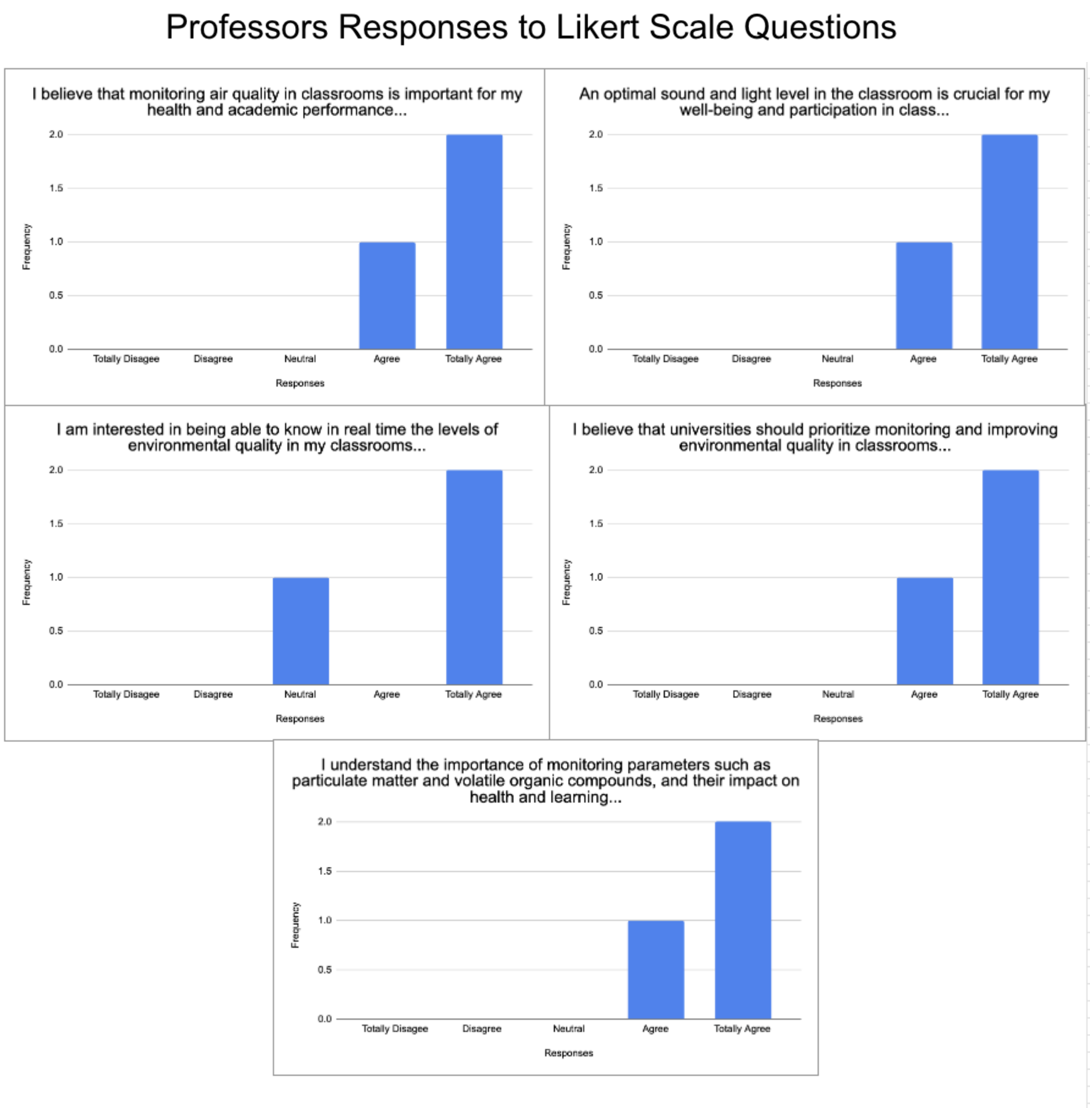


Figure 20 – Professor responses to five Likert-scale questions evaluating perceptions of air quality monitoring, optimal lighting and sound conditions, interest in real-time environmental data, prioritization of environmental improvements, and understanding of airborne pollutants' impact on learning.

"In larger classes, the room feels heavier, warmer, and louder. Ventilation and air quality make a real difference." - Professor 3

Professors also proposed solutions to improve conditions, such as upgrading acoustic panels, improving window insulation for better temperature control, and implementing real-time environmental monitoring tools, especially in spaces prone to heavy chemical use or high noise exposure.

4.1.3 Researcher Responses

To broaden the perspective on indoor environmental factors in university settings, three researchers were interviewed. Although their primary research fields focused on biomedical engineering, bioengineering, and control systems, the interviews centered on their experiences and observations regarding classroom and laboratory environmental conditions, rather than the direct impact on their research.

Researcher 1, who specializes in clinical decision support systems and biomedical data analysis, reported primarily working in indoor environments, including classrooms and laboratories. She noted that environmental factors such as gas quality in laboratories and air circulation in classrooms could play a critical role in maintaining student well-being and focus. She suggested that real-time feedback systems or environmental surveys placed near classroom entrances could help monitor and improve these conditions.

Researcher 2, currently conducting a doctoral study in bioengineering and artificial intelligence related to respiratory health, emphasized the importance of monitoring air quality indicators such as PM, VOCs, and CO_2. She explained that high concentrations of these pollutants, especially in poorly ventilated classrooms, could negatively affect students' cognitive performance and overall classroom experience, particularly during high-temperature periods.

Researcher 3, who focuses on the technical aspects of environmental monitoring systems, highlighted the relevance of measuring CO_2 levels, temperature, and humidity in educational environments. He noted that overcrowded classrooms could lead to elevated indoor pollutant levels and discomfort, which may impair student concentration. He proposed improvements such as reducing class sizes and enhancing classroom ventilation systems.

Overall, the researchers agreed that indoor environmental monitoring could serve as a valuable tool for improving student comfort, concentration, and academic performance. Their insights support the broader argument that factors such as air quality, temperature, humidity, and noise should be systematically assessed and managed within academic institutions.

4.1.4 University Staff Responses

To better understand the operational perspective behind classroom environments, two university staff members responsible for infrastructure and audiovisual systems were interviewed. Their insights provided a practical view of how environmental conditions are monitored, managed, and experienced on campus.

Staff Member 1, who works in energy efficiency and infrastructure management, focused primarily on temperature and humidity regulation. He shared official recommendations for climate control across university buildings, which included operating guidelines for heating and cooling systems based on external temperatures. Facility heating systems activate generally between November and March when outdoor temperatures fall below 18°C, while air conditioning systems operate between June and September when temperatures exceed 27°C. Indoor temperatures are expected to be maintained above 23°C during cooling seasons, with a relative humidity between 30% and 70%. Staff Member 1 emphasized that these measures aim to balance energy efficiency, student health, concentration, and cost control, although he noted that economic constraints sometimes limited full implementation. He also pointed out that his role is to provide recommendations and enforce parameters, but he does not directly manage day-to-day classroom climate control.

Staff Member 2, responsible for managing audiovisual and telepresence technology across classrooms, addressed environmental issues from the perspective of audio and visual quality rather than air quality or temperature directly. He observed that while temperature is usually not critical for equipment functionality, poor acoustics and background noise present frequent challenges, particularly when trying to record or broadcast lectures. He explained that technical failures in audiovisual equipment, such as microphones, projectors, and recording systems, severely disrupt classroom operations. Staff Member 2 highlighted that inadequate acoustic insulation in classrooms, along with poor classroom design (such as overly long rooms), negatively impacts both in-person and remote learning experiences. He recommended improving acoustic isolation, furniture comfort, lighting conditions, and overall classroom layout to foster a more motivating and productive environment for students.

Both university personnel agreed that environmental conditions, whether thermal, acoustic, or ergonomic, play a crucial role in the quality of the classroom experience. However, they differed in the extent to which real-time environmental monitoring would assist their work: Staff Member 1 viewed it as important for broader health and energy management goals, while Staff Member 2 saw limited direct relevance to his audiovisual operations, although he acknowledged that better environments could indirectly benefit student motivation and attention.

Their Likert-scale responses (Figure 21) reflected this split. Staff Member 1 strongly supported environmental monitoring for health, well-being, and academic improvement. Staff Member 2 recognized its importance more for the students' experience than for his own job role, noting that environmental comfort factors like acoustics, seating, and lighting are critical for creating an effective learning atmosphere.

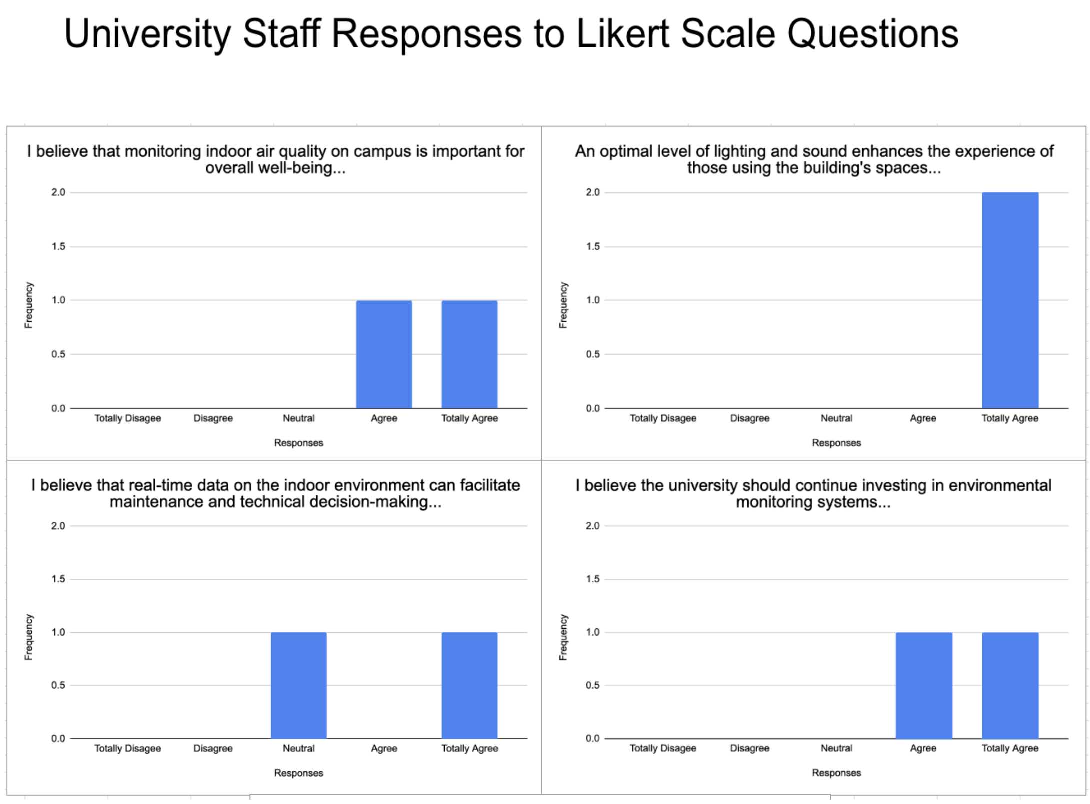


Figure 21 – Staff responses to five Likert-scale questions evaluating perceptions of air quality monitoring, lighting and sound conditions, real-time environmental data interest, the university's prioritization of environmental factors, and awareness of airborne pollutants' impact on student health and learning.

4.2 Quantitative Data

Once the modules were deployed, data was continuously collected from April 20th, 2025 to April 30th, 2025. This data was analyzed using the dashboard, pictured in Figure 23, and extracted statistical metrics are pictured in Table 2. A baseline pattern was used to validate the system was operating properly: Light increased at sunrise and decreased at sunset, with workdays having higher lux due to lights being turned on. Pressure stayed constant, while temperature and humidity fluctuated within normal ranges in accordance with the weather. Other than some notable exceptions, every condition stayed within reasonable bounds.

Although the air quality was within an acceptable range for a majority of the sampling duration, there were short but intense periods of poor air quality. These included massive spikes in PM1, $PM_{2.5}$, and PM_{10}, as well as more gradual but long lived gaseous indicators of decreasing air quality such as CO, NO_2, and NH_3.

The temperature levels recorded are slightly higher than the real temperature in the room, as further calibration is required that time constraints did not allow for in our deployment phase. The patterns are representative of the real values, but the running temperature of the central processing unit (CPU) increased the sensor's readings and should be fixed in future iterations of this work.

The Nitrogen Dioxide, Carbon Monoxide, and Ammonia sensors are special cases in this module. These sensors do not have a specific unit of concentration, as they pick up different types of gases that may interfere with the readings. Instead, they output internal sensor resistance (k0). This value is associated with a concentration of the listed gases, but the true concentration can vary depending on the environment the readings are taken in. Therefore, instead of comparing our readings to acceptable levels for these environmental factors, we will note whether larger or smaller values are better, and use the collected data to analyze the changes in air quality.

The environmental factor that violated acceptable levels most consistently was humidity. On average, the sensor was reading a humidity level of 26.65%, below the suggested minimum of 30%. With a standard deviation of 4.47%, this level was fairly consistent, and shows that the humidity levels of the lab are slightly too low in general to be considered comfortable.

Table 2 – Analytics of each collected environmental factor from 9 a.m. - 5 p.m. over data collection period

		Acceptable Range	Mean	Standard Deviation	Min	Max
Humidity	%	30-60	26.65	4.77	15.1	48.85
Nitrogen Dioxide (N_20)	k0	Unknown - smaller is better	38.14	9.06	3.23	178.22
Carbon Monoxide (CO)	k0	Unknown - larger is better	176.31	15.22	139.56	308.5
Ammonia (NH_3)	k0	Unknown - larger is better	208.75	37.15	6.35	290.07
Light	Lux	300-500	165.30	199.25	0.83	704.20
Temperature	°C	18-25	28.73*	2.45	20.48	32.69
Particulate Matter (PM_1)	µg/m³	0-2	1.25	4.15	0	78
Particulate Matter ($PM_{2.5}$)	µg/m³	0-12	2.36	7.27	0	142
Particulate Matter (PM_{10})	µg/m³	0-54	2.63	7.91	0	164

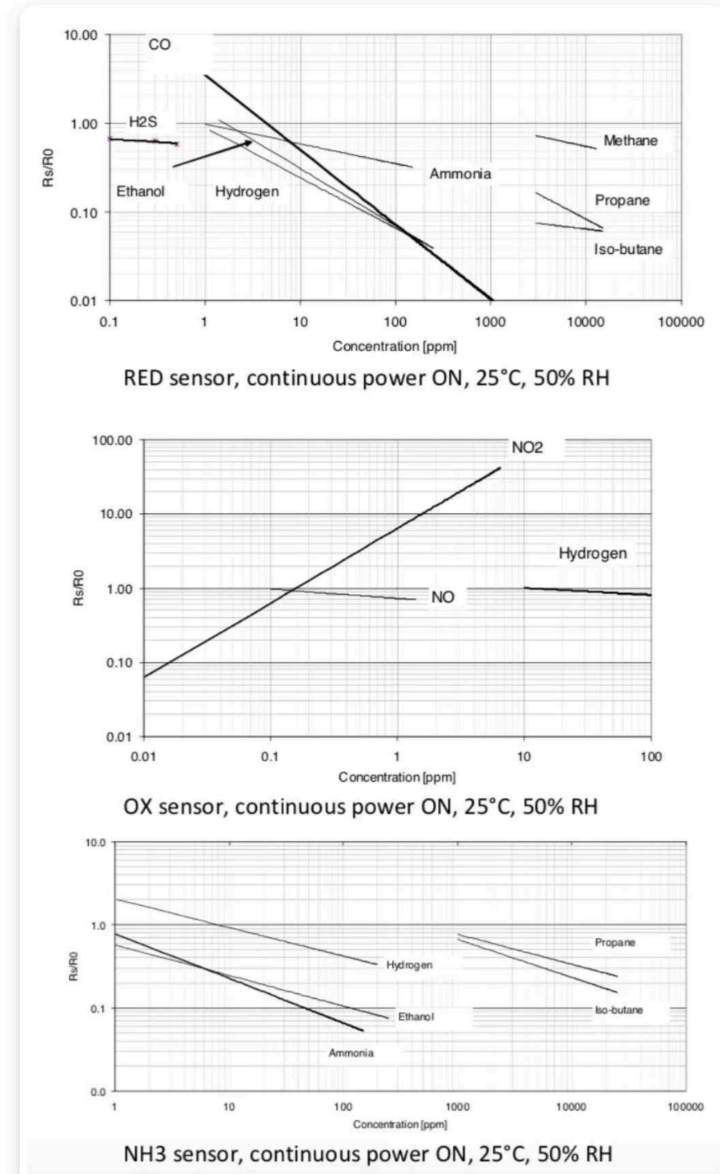


Figure 22: MICS6814 Internal Resistance vs PPM Graphs

Figure 23 - Graphs on dashboard displaying data collected from Friday, April 24, 2025 - Saturday, April 25, 2025

5. Discussion

5.1 Perceived Impact

5.1.1 Environmental Conditions

The findings from interviews and survey responses revealed clear and recurring perceptions among students, professors, researchers, and faculty regarding how environmental conditions shaped the university learning experience. Although each group engaged with the classroom environment differently, their observations aligned in key areas, highlighting persistent discomfort, lack of awareness, and a disconnect between existing infrastructure and the daily realities of teaching and learning.

Across all interviews, temperature emerged as a central issue. Students frequently described classrooms that were either too cold in winter or too hot during warmer months, with little consistency across spaces. These experiences were often linked to the building's design, particularly large exterior glass panels, which allowed for excessive heat gain or loss depending on the season. While the university operated heating and cooling systems on a set schedule, students were often unaware of when or how those systems functioned. Notably, none of the students interviewed had access to or knowledge of real-time temperature readings in their classrooms, which limited their ability to advocate for change or adjust their behavior. Professors echoed these concerns, observing that thermal discomfort diminished student attention and participation, particularly in larger, crowded classrooms.

Survey responses reinforced these patterns, as most students selected options indicating discomfort with temperature conditions and a strong interest in tools that could provide real-time environmental feedback. Although the survey questions were not open-ended, the consistent agreement across responses signaled that students recognized temperature as a critical factor in their ability to learn effectively.

Similar themes emerged around air quality, although students struggled to describe it in technical terms. Instead, they relied on physical sensations, using words like "heavy" or "dense" to describe classrooms that lacked ventilation, especially those shared with many students or used for laboratory work. Interviews revealed that these sensations became more noticeable during long lectures or in spaces used for soldering, woodworking, or chemical handling. Students reported that odors lingered in the air and created discomfort, yet none expressed familiarity with how air quality could be measured or whether their classrooms had any monitoring systems in place. Professors and researchers noted the same issue, particularly in lab settings where air extraction was insufficient or poorly localized.

In both interviews and surveys, students also emphasized noise as a major source of distraction. The opening of doors for ventilation, often a workaround for poor air circulation, allowed sound from hallways, adjacent classrooms, and the nearby cafeteria to disrupt learning. Participants described classrooms as acoustically porous, with conversations, moving chairs, and machinery noise frequently bleeding into instructional periods. Professors described this issue as particularly problematic when classrooms were located in high-traffic areas or when lecture halls lacked proper insulation. An engineering professor with expertise in acoustics proposed specific improvements like insulated windows and structural separation of loud equipment from quiet study zones, underscoring that these concerns are well understood but remain unresolved in practice.

Unlike temperature or noise, lighting conditions received relatively little negative feedback. Most students expressed satisfaction with classroom lighting and only became more critical when prompted during interviews. Preferences varied: some students favored cooler light tones for focus, while others preferred warmer lighting for comfort. Natural light was generally preferred over artificial sources, particularly in morning classes. Although not considered a major impediment, students did acknowledge that lighting affected their mood and concentration, especially during the shorter daylight periods of winter.

Room occupancy surfaced as a compounding factor that worsened other environmental discomforts. Both interviews and survey responses indicated that crowded classrooms created a buildup of heat, noise, and odors. These effects were particularly pronounced in high-demand courses like fluid mechanics, where class sizes could exceed 100 students. Researchers and professors described this as an architectural issue, with oversized groups placing disproportionate strain on already limited ventilation and acoustic controls.

Throughout the study, a common thread emerged: students and faculty consistently expressed a desire for greater awareness and agency over their physical learning environments. Whether through access to real-time environmental data, better-designed classrooms, or structured feedback opportunities, participants indicated that they were willing to engage with these issues, but lacked the tools to do so. Importantly, the perception of environmental discomfort was not limited to anecdotal complaints; it reflected a shared understanding that these conditions were affecting focus, energy, and academic engagement.

5.1.2 Perspectives Across Stakeholders

While students provided the most consistent feedback across interviews and surveys, professors, researchers, and faculty members offered critical contextual insights that highlighted both operational constraints and disciplinary perspectives on classroom conditions.

Among professors, there was general agreement that environmental discomfort impacted student focus and engagement, though not all viewed it as a direct threat to learning outcomes. One professor with expertise in acoustics argued that student interest and intrinsic motivation outweighed environmental factors, although he acknowledged that noise and temperature fluctuations could hinder participation. In contrast, two other professors, both teaching technically intensive courses, asserted that poor thermal and acoustic environments directly undermined classroom dynamics. They described how student attention declined in overheated or poorly ventilated rooms and how concentration suffered during moments of excessive noise or odor exposure. These interviews highlighted a divide: while some faculty perceived environmental issues as peripheral, others viewed them as central to the teaching-learning process, particularly in courses that already challenged students' cognitive load.

Researchers, though less focused on classroom teaching, emphasized the scientific and health-related implications of poor air quality and thermal comfort. A doctoral researcher specializing in respiratory health outlined how high CO_2 levels and volatile organic compounds can impair cognitive performance, particularly in overcrowded or poorly ventilated rooms. Another researcher pointed to the need for fume extraction systems in labs and soldering areas, noting that shared workspaces without proper air control can expose students and researchers to long-term risks. Researchers also expressed strong interest in real-time environmental data collection, not just for academic curiosity but for its potential to guide infrastructure improvements and promote safer learning environments.

In contrast, faculty staff responsible for infrastructure and audiovisual systems approached the issue from a practical standpoint. One staff member described the university's heating and cooling protocols, which operate on fixed seasonal guidelines tied to outdoor temperatures. He acknowledged that while these systems aim to balance comfort and energy efficiency, limited funding and building design constraints reduced their effectiveness. Importantly, he confirmed that daily classroom climate control was not managed directly by his office, revealing a bureaucratic gap between environmental regulation and its implementation. Another faculty member, focused on audiovisual technology, stressed that noise interference was a routine challenge, especially in large or poorly insulated classrooms. While not responsible for air or temperature systems, he noted that acoustics significantly affected the quality of recorded lectures and real-time communication, both increasingly vital in hybrid learning environments.

Together, these stakeholder insights painted a fuller picture of the institutional landscape. Students called for transparency, adaptability, and comfort. Professors sought environments that supported engagement without constant distractions. Researchers identified environmental metrics linked to health and cognitive performance. Staff worked to implement operational policies within existing resource limitations. Despite differing roles and priorities, all groups implicitly supported the idea that learning environments should be more responsive to human needs.

This alignment suggests that environmental discomfort is not merely a passive inconvenience but an active barrier to teaching, learning, and well-being. The consistency of stakeholder concerns strengthens the case for implementing smarter, real-time monitoring tools and participatory feedback systems, not as luxury upgrades, but as necessary steps toward more inclusive and effective educational spaces.

5.2 Trends in Data

Upon analysis of the data collected by the SLE system, we found that some unpredictable patterns could be explained by actions taken by the inhabitants of the lab. The biggest surprise to us when interpreting the graphs were the sudden spikes in particulate matter concentration, followed by long periods of higher CO, NO_2, and NH_3 levels in the air. We attempted to explain this pattern by discussing what each person in the lab was doing at the times of the spikes in particulate matter concentration. We found that the levels of different types of particulate matter increased drastically when one of our team members was soldering sensors to a board. The fumes released by lead-based solder consist of particles and gases that can be harmful when inhaled, causing short-term discomfort and long-term health hazards. This explains why the SLE system is reading a spike in Particulate Matter and gases during periods of active soldering. However, the PM levels returned to normal when the school was inactive, since there was no active soldering occurring.

5.3 Awareness & Aversion

Through both interviews and comments from surveys, a common expression of unclear understanding emerged of what Air Quality was or what the purpose of SLE was. These sentiments were not a majority, but individuals did make their feedback known.

5.4 Nuanced Variables

While quantitative measurements offer some insight into the quality of the classroom environment, deeper nuances exist for each unique variable. Our interview with a senior acoustics researcher revealed that not only was decibels an important unit of sound, a multitude of other measurements can describe it in further detail. These include domains such as Level (can be measured in dB), Amplitude, and Frequency, and LAF maximum/minimum,=, _, _, and _, each of which can help understand how noise in a classroom may be affecting students. A dashboard of the researcher’s analysis process is shown below (Figure 24). An important question they may be able to answer is, are these loud sounds a professor talking out of a speaker? Or high pitch buzzing caused by faulty machinery?

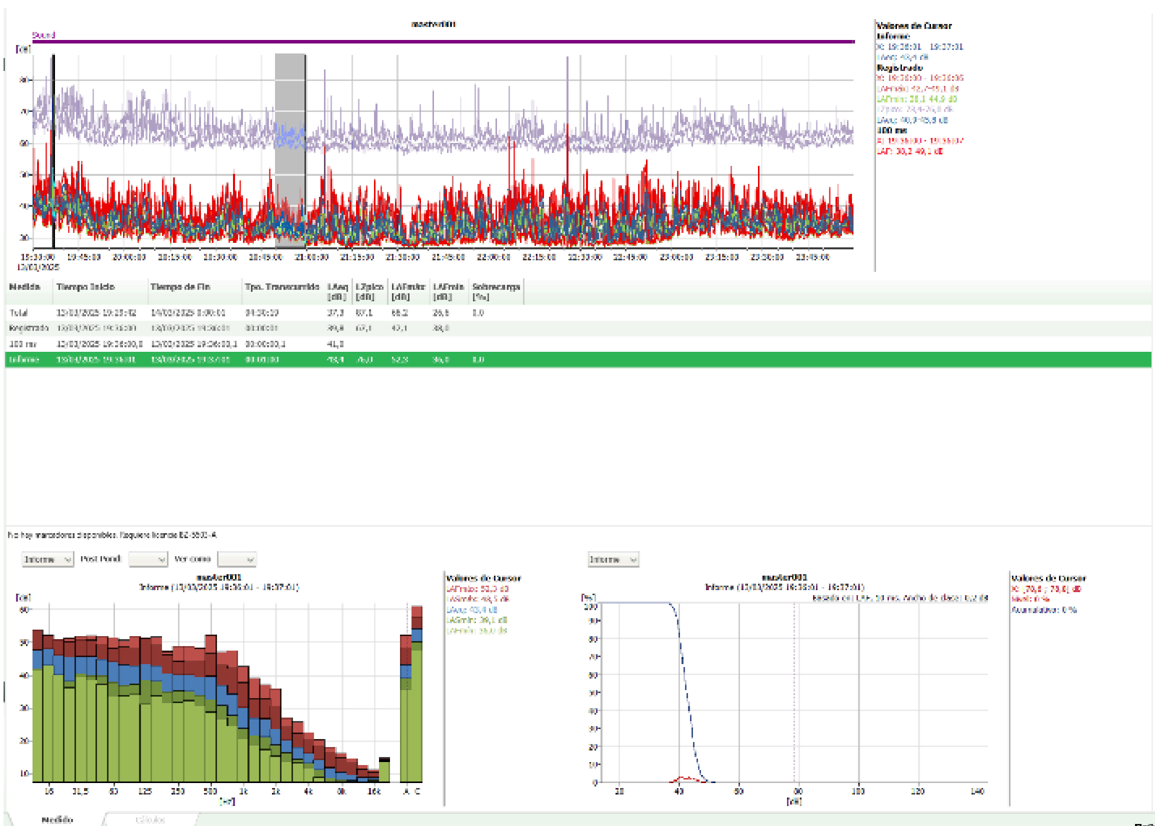


Figure 24 – In-depth graphical acoustic analysis using an expensive instrument and proprietary software

6. Conclusion

The SLE project has successfully developed a modular device capable of providing valuable insights into its surrounding environment. This type of data collection allows for a wide range of future applications, including real-time monitoring of classroom conditions to optimize learning environments and informing data-driven decisions in educational infrastructure planning.

6.1 Recommendations

While the Smarter Learning Environments initiative successfully met its core objectives and delivered reliable environmental monitoring in classroom settings, several areas for future improvement emerged through stakeholder feedback and hands-on implementation. Opportunities to enhance the project's accuracy, efficiency, and long-term impact include refining sensor calibration for more precise measurements, reducing the time required for circuit assembly, and improving both the resolution of environmental data and the device's mobility and network capabilities. In parallel, the qualitative insights gathered from students, professors, researchers, and staff highlighted persistent discomfort and limited user agency in managing classroom conditions. Together, these findings point to a clear need for adaptive, transparent, and human-centered strategies to enhance classroom comfort and learning environments more broadly.

6.1.1 Institutional Improvements

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University staff and facilities managers should consider implementing adaptive systems that give occupants more control over environmental conditions without compromising energy efficiency mandates. Smart thermostats with visible, user-friendly interfaces could provide greater transparency and allow for temperature adjustments within a controlled range, particularly in classrooms that experience seasonal discomfort. Introducing localized displays showing current conditions such as temperature, humidity, and air quality, would give users immediate context and encourage awareness, while remaining aligned with institutional guidelines on energy use.

The SLE project can also support more proactive use of environmental data by facilities teams. The system's monitoring capabilities could inform adjustments to HVAC schedules, lighting routines, or classroom assignments, particularly during seasonal transitions when environmental discomfort tends to peak. By focusing on classrooms as well as specialized spaces such as acoustic, chemical, or mechanical laboratories (where conditions like air quality, noise, and lighting can directly influence academic performance) this project highlights how targeted data collection can support informed renovation efforts. These might include improved insulation, acoustic dampening, or upgrades to ventilation systems in the most affected areas.

6.1.1.1 Air Quality

Classrooms and laboratories would also benefit from more robust air circulation strategies. Real-time air quality sensors could make otherwise imperceptible factors such as elevated CO_2 or VOC levels visible and actionable. These systems should be accompanied by intuitive visual indicators like color-coded alerts and paired with natural ventilation options, such as operable windows where possible. In environments where emissions from activities like soldering or chemical handling are unavoidable, the installation of localized fume extraction systems or designated technical spaces could minimize exposure for surrounding occupants and improve overall air conditions.

6.1.1.2 Acoustics

Acoustic comfort also remains a critical area for improvement. Reducing cross-room sound transmission through acoustic panels, insulated doors or windows, and careful spatial zoning of high-noise activities like machining, 3D printing, or group collaboration areas, would help create more focused learning environments. Enclosures for noisy equipment like 3D printers and laser cutters could offer dual benefits, mitigating both airborne contaminants and noise levels. While lighting conditions were not a primary concern, installing sensors that monitor and display light intensity and temperature may still provide valuable insights and customization options, especially in multipurpose classrooms.

6.1.1.3 Occupancy

Classroom occupancy emerged as a key factor that exacerbated many environmental issues. To mitigate this, course scheduling could be adjusted to reduce the number of students in individual sessions, especially for high-demand or technically intensive subjects. Offering multiple sections of these courses would ease environmental strain, reduce noise, and support better air circulation and comfort for both students and instructors.

6.1.2 Guidance For Future Research Teams

For future project teams, early engagement with stakeholders is essential. Identifying and contacting interview candidates in advance allows for tailored, relevant data collection and enables broader inclusion of voices beyond students such as faculty, maintenance personnel, and technical staff. Including these groups in perception-based surveys would help capture a fuller picture of daily operational constraints and infrastructural needs. Additional factors such as furniture design and acoustic properties also deserve consideration. Replacing loud, movable chairs with quieter, ergonomically conscious alternatives could reduce ambient noise and improve concentration.

Finally, future teams may consider piloting a simple, recurring feedback mechanism such as a daily digital survey, so that student comfort can be continuously monitored throughout the academic year. This approach would create a living dataset of occupant experience and provide facilities teams with actionable insights in real time. Moreover, the environmental monitoring framework developed in this project holds potential beyond traditional academic spaces. Similar systems could be adapted for use in medical centers, museums, cafeterias, or any setting where air quality, noise, and comfort directly impact occupant health and productivity. Exploring these extended applications may broaden the relevance and utility of future research in this field.

6.1.3 Sensor Characterization

While the Enviro+ sensor suite and software library reports environmental variables with units built in, cheaper sensors require calibration or may not even use human-readable units, such as Analog to Digital Converter (ADC) voltage values. The Enviro+ can be used to take baseline readings and build an equation for undocumented sensors to report reasonable units by interpolation. This process can be done in two steps: mapping known readings to an uncharacterized sensor, and building an equation to interpolate between known readings. The first step consists of taking readings with both sensors at the same time with varied measurements, preferably throughout the entire range of reasonable values a few times. Next, an equation must be built to estimate new values between known points. Understanding the nature of the variable to be measured and the sensor itself can help determine what kind of interpolation is best applied, either linear, exponential, or logarithmic.

6.1.4 Circuit Assembly Inefficiencies

While the units themselves are highly modular and configurable, a disproportionately significant amount of time was put into the wiring. We recommend an automated solution to relieve some of the time investment, such as PCB design to simplify the process into ordering a finished product instead of the tedious and manually intensive process of building module wiring from the ground up. Unlike the process of printing the module housing, which consists of a set-and-forget 3D print job that takes roughly nine hours with no human intervention followed by a few minutes of post-processing and assembly, wiring and soldering can take a team member days to weeks, especially if iterative redesigns are called for.

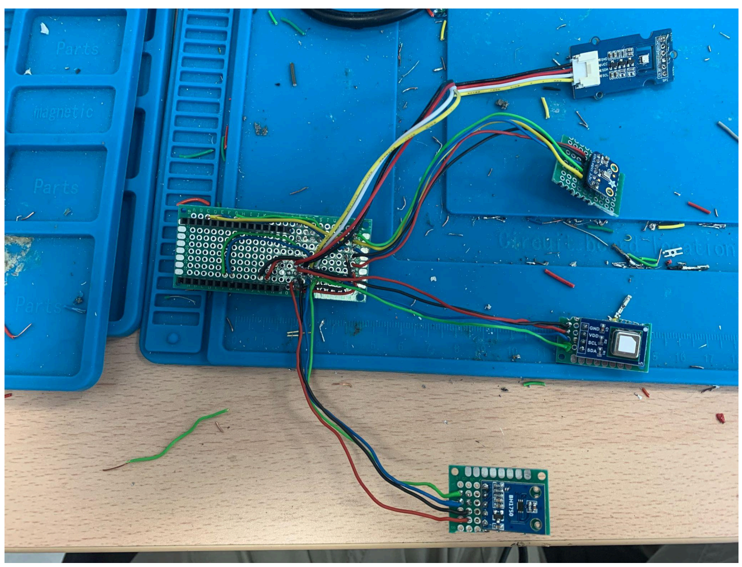

Figure 25: Soldered Board with Sensors and Wires

6.1.5 Measurement Resolution

The module and servers are robust enough to support multiple readings per second, but environmental measuring applications do not require this resolution. The measurement resolution can be lowered in one of three ways: module-side, server-side, or client-side. Each has its own benefits and drawbacks. The simplest and easiest to implement would be module-side, where each module keeps a high measurement resolution locally, but only reports the average of a period (say, ten minutes) back to the server. This option will improve performance of the web client, which can experience some slowdown when attempting to fetch large ranges of data. This may, however, lead to the loss of some important information. For example, a sudden spike in noise for a minute may be smoothed over in the report. This can be resolved by sending more detailed summaries, or choosing a different resolution method. Using lower resolution on the server or client side allows for the same end result for the user, while also keeping the option for dynamically sized time windows or creation of more advanced summaries instead of losing important data if the modules are missing or have inadequate code. These advanced summaries may include the median, range, finding quartiles or standard deviation, looking for values outside a threshold, or any query a user may request.

6.1.7 Mobility and Networking Improvements

Each module is small and quite mobile already, and can be easily moved or packed without need to worry about damage in transit. However, the networking setup inside the university leaves some room for improvement, with the server and modules living on a custom subnetwork/LAN on a router. There are several ways to improve this: refine wifi configuration, setting up a cloud server, and using a module as a network AP/bridge. Since the modules were deployed in a university, the eduroam network available at secondary institutions is available for use, although the connection using a security protocol with a certificate was not a priority of the project. While the modules function properly in the locations deployed, they can only be connected near the router with network security consisting of only SSID and password.

In locations or applications without reliable internet access (or a network with more security than SSID and password), the Raspberry Pi is able to be configured as an internet access point, with the network in bridge mode. Since it has onboard long-term storage in the form of an SD card, the backend can be modified to run onboard and store data as storage permits until it can be migrated to the server using the import/export CSV (comma separated values) feature.

Locations and applications without easy access to power are supported as well. The Arduino MKR Wifi 1010 natively supports Li-Po batteries with a built-in port. We were able to test a short duration with a small portable battery, however it was not long enough to properly determine how long it would continue functioning properly.

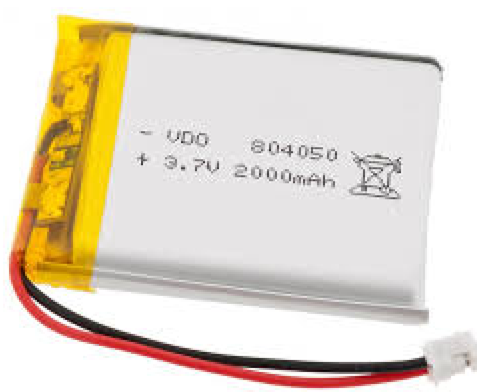

Figure 26 – 3.7V Li-Po Battery

The final improvement to the networking and software infrastructure in general is migrating the services to a cloud host. Building containerized docker images allows for easy migration and deployment to new machines or even cloud hosting providers.

Keeping the containers running in the cloud instead of the server living on a physical computer on the local network would allow incoming connections from devices on separate networks, so modules could be placed in multiple locations, or clients could connect to the website from wherever they chose. A cloud host would also be able to scale resource usage dynamically, such as automatically allocating more data storage or more processing power for heavier workloads.

6.1.8 System Expansion

The SLE system was designed with portability and modularity as key values, meaning expansion and adaptation to other types of environments is possible. Important design decisions that have allowed for this level of adaptability have been made in the development of both hardware and software.

In hardware development, we chose to create a housing with trays that was designed to allow for the attachment of several different types of sensors and microcontrollers. This approach supports rapid prototyping and easy replacement of individual components without the need for redesigning the entire system. Each tray is created to securely hold specific sensors or microcontrollers, ensuring proper alignment for reliable electrical connections. This design facilitates testing of different configurations, making the module versatile for both development and deployment phases.

On the software side of the system, we chose to configure the database in a manner that did not restrict users to a classroom environment. System administrators may upload an image of their floor plan or room, with no strict limitations on how they decide to represent their environment. For example, in our testing we have used the floor plan of a university laboratory. Other implementations can use a picture taken of a room, a blueprint of a building, or any other type of image.

We hope that this system will be used with wider applications in the future, and have made these decisions with that goal in mind.

7. Appendix

7.1 Glossary of Terms

ADC - Analog-Digital Converter

CO - Carbon Monoxide

CSS - Cascading Style Sheets

CSV - Comma separated values

HTML - Hypertext Markup Language

HVAC - Heating, Ventilation, Air Conditioning

INiBICA - Instituto de Investigación e Innovación en Ciencias Biomédicas

JSON - JavaScript Object Notation

LAN - Local Area Network

Li-Po - Lithium Polymer

LoRa - Long Range

NH_3 - Ammonia

NO_2 - Nitrogen Dioxide

PCB - Printed Circuit Board

PIR - Passive Infrared

SKOMOBO - School Monitoring Box

SLE - Smarter Learning Environments

SSID - Service Set Identifier

UART - Universal Asynchronous Receiver/Transmitter

UCA - Universidad de Cádiz

UI - User Interface

USB - Universal Serial Bus

VOC - Volatile Organic Compound

7.2 Contribution Statement

Subject	**Contributors**
Social	
Interviews	Alejandra Galvez, Diego Canovas
Translation	Alejandra Galvez
Survey	Alejandra Galvez, Diego Canovas, Jacob

	Burns
Results Analysis	Alejandra Galvez
Hardware	
Circuit Design & Assembly	Diego Canovas
Modeling & 3D Printing	Diego Peña-Stein
Software	
Front End	Jacob Burns
API	Jacob Burns, Diego Peña-Stein
Back End	Diego Peña-Stein
Software Infrastructure & Deployment	Diego Peña-Stein, Jacob Burns
Embedded Programming	Diego Peña-Stein, Diego Canovas

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7.4 Supplementary Materials

Code repository via GitHub: https://github.com/Smarter-Learning-Environments

Module housing design via Onshape:

https://cad.onshape.com/documents/436982d1552209b05311e99b