

ARDUINO-BASED ELECTRONIC MODULE FOR OPTIMIZING AIR CONDITIONING SYSTEMS

*Sérgio Costa Martins de Alencar¹, Robson Uitalo dos Santos Costa²,
Manoel Pedro Lima de Almeida³ e Silva e Guilherme Bednarski Benedetto⁴*

ABSTRACT

This paper presents the development of an electronic module based on the Arduino platform aimed at optimizing indoor climate control systems. The device uses a PIR sensor to detect the absence of occupants and, after a configurable interval, activates an infrared emitter responsible for automatically turning off air conditioners. The proposed solution, which is low-cost and easy to implement, seeks to reduce electricity consumption without compromising thermal comfort, contributing to sustainability by avoiding waste and reducing carbon emissions. To assess its potential impact, the RedEE Public Buildings energy audit method was applied, estimating the energy savings and reduction in costs and CO₂ emissions that could be achieved in air-conditioned environments in a public building. The project responds to the demand for affordable automation alternatives, especially suitable for medium and small buildings, where commercial solutions are not feasible. It is hoped that the technology developed will encourage more efficient energy practices and promote the spread of affordable smart systems for energy consumption management.

Keywords: Energy transition; energy efficiency; air conditioning systems.

¹ Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM. E-mail: sergio.alencar@ifam.edu.br

² Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM. E-mail: 2023325000@ifam.edu.br.

³ Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM. E-mail: 2023322985@ifam.edu.br

⁴ Instituto Federal de Educação, Ciência e Tecnologia do Amazonas – IFAM. E-mail: 2023322250@ifam.edu.br

1. INTRODUCTION

The quest for greater energy efficiency in buildings has become a fundamental strategy for reducing operating costs and mitigating the environmental impacts of electricity consumption. In particular, public buildings offer significant potential for savings, since a large part of their energy demand is associated with air conditioning systems, such as air conditioners, which often operate wastefully when rooms are unoccupied (Ortiz-Peña; Honrubia-Escribano; Gómez-Lázaro, 2025). In this context, low-cost automation solutions emerge as viable alternatives to optimize the use of these systems and contribute to sustainability. The implementation of automation systems allows air conditioning devices to be automatically turned off when there are no occupants, reducing electricity consumption without compromising thermal comfort (Merabet et al., 2021). In addition to reducing consumption, this approach also helps reduce carbon dioxide (CO₂) emissions, aligning with global decarbonization goals and the need for more responsible energy practices.

This paper presents the development of an electronic module based on the Arduino platform, designed to improve the efficiency of air conditioning systems in indoor environments. The solution was evaluated using the Energy Efficiency Network in Public Buildings (RedEE) energy audit method (RedEE, 2025), which enabled estimating potential electricity savings in a public building, as well as the resulting reductions in costs and CO₂ emissions (Chen; Yin, 2022). Thus, this study seeks to advance affordable automation alternatives, especially in medium- and small-sized buildings, where commercial solutions from major brands are often economically unfeasible.

2. THEORETICAL BASIS

Energy Transition

The energy transition is a global process aimed at replacing polluting energy sources with cleaner, more sustainable alternatives (ANEEL, 2025). Currently, this change is directly linked to combating climate change and reducing emissions of gases such as CO₂ (Geweda et al., 2025). This transition to renewable energy, such as solar and wind power, is essential to mitigate the environmental impacts of non-renewable sources. Despite its importance, the transition faces significant challenges. The sector's reliance on fossil fuels is a major obstacle, making the phase-out of these fuels a complex and challenging task (Ide, 2020).

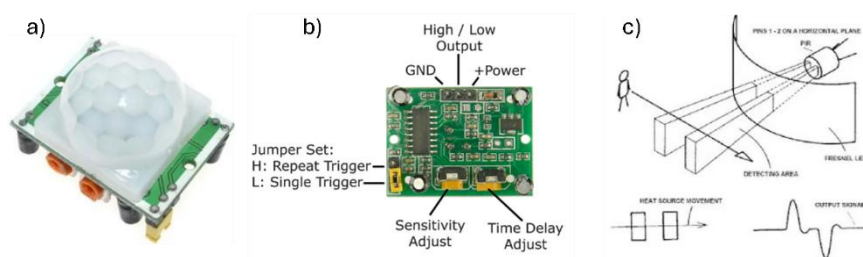
Energy Efficiency in Public Buildings

Energy efficiency is defined as the ratio of useful energy delivered to total energy consumed, but its advancement faces technical, economic, and behavioral barriers. Increasing the current pace of progress in energy efficiency actions is not easy, as additional gains become harder to achieve as lighting and air-conditioning technologies approach their limits (Belaïd, 2025). Thus, the concept should be viewed not only in technical terms but also as shaped by public policies and social factors. In public buildings, energy efficiency is highlighted due to high consumption and the potential to serve as a model of sustainability for other sectors of society. Measures adopted in universities, such as modernizing air conditioning systems, replacing lighting with LEDs, reinforcing thermal insulation, and using renewable energy, significantly reduce energy intensity and emissions. Thus, applying efficiency strategies in public buildings represents not only savings, but also environmental and social benefits (Ortiz-Peña; Honrubia-Escribano; Gómez-Lázaro, 2025).

PIR Sensors

PIR (Passive Infrared) sensors are used in automation and security to detect movement. They work by identifying changes in infrared radiation from warm bodies, such as people. For this reason, they are commonly found in automatic lighting systems, alarms, and IoT devices (Guinther, 2018). The HC-SR501, shown in Figure 1, is a popular PIR sensor model. It is low-cost and easy to use with microcontrollers, operating at voltages from 4.5V to 12V. This model uses two pyroelectric sensors to detect motion more accurately, distinguishing real motion from thermal noise (PIR, 2025). Recent research highlights its integration with platforms such as the Android Open Source Project (AOSP) for automated environment control (Oliveira, 2025).

Figure 1 – HC-SR501 PIR sensor – (a) Top view, (b) Bottom view with pinout, (c) Differential detection

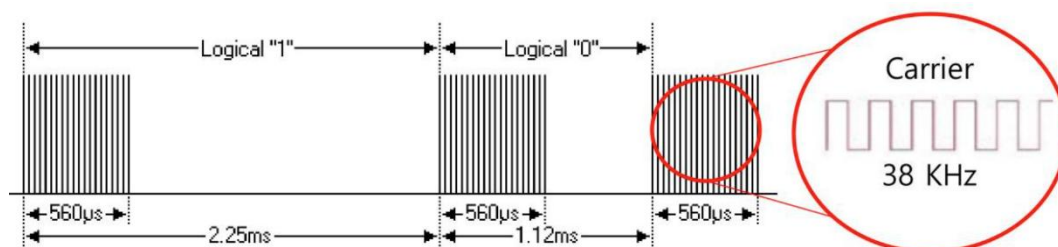


Source: PIR, 2025.

IR signaling for air conditioner control

Infrared remote control devices (CIRs) use encoding protocols to convert commands into optical signals. The NEC (Nippon Electric Company) protocol, illustrated in Figure 2, is one of the most widely used and is based on pulse distance coding modulation, employing a carrier of approximately 38 kHz. Each bit is represented by a 560 μ s pulse followed by a distinct time interval: 2.25 ms for the "1" bit and 1.125 ms for the "0" bit. (Kim; Suh, 2021).

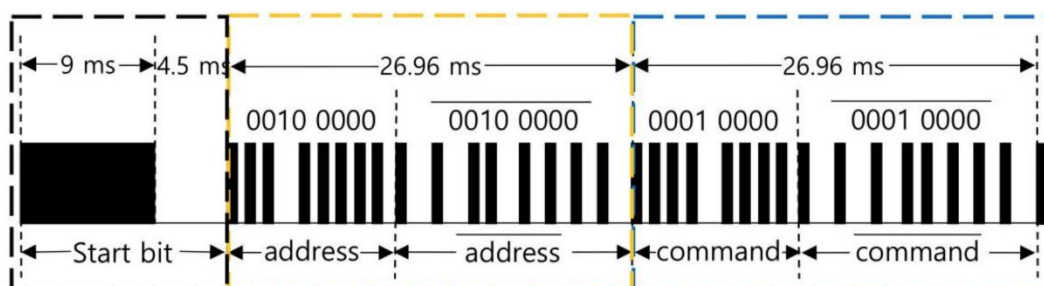
Figure 2 – Modulation by pulse distance coding of the NEC protocol



Source: Kim; Suh, 2021.

The typical message structure begins with a synchronization pulse of approximately 9 ms, followed by a 4.5 ms pause. It continues with eight address bits and their inverted forms, as well as eight command bits and their inverted forms. The packet ends with a 562.5 μ s pulse that marks the end of the transmission, as shown in Figure 3.

Figure 3 – Message structure in the NEC protocol.



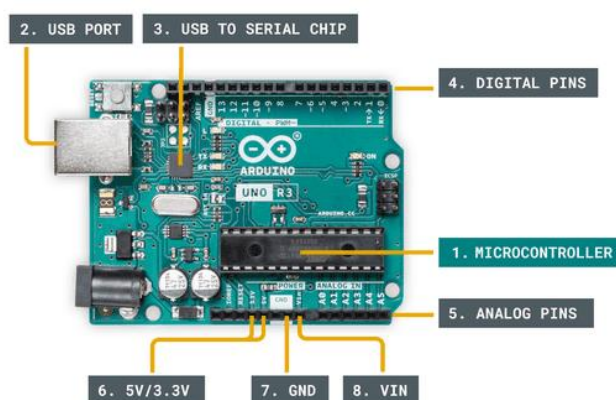
Source: Kim; Suh, 2021.

The NEC protocol is robust because it uses address and command redundancy to detect errors and increase reliability. Its implementation is simple, suitable for microcontrollers and integrated circuits, and its industrial adoption ensures compatibility between various devices. On the other hand, the protocol has some limitations. Transmission is slow due to long interval encoding, limiting efficiency to a few hundred bits per second. Precise timing increases the risk of errors in noisy environments, and restrictions on address and command formats make complex applications difficult. The NEC protocol has no authentication or encryption, making signals susceptible to interception, especially in IoT applications. Recent literature highlights that these limitations must be considered in modern designs, as the use of infrared protocols such as NEC increases the risk of interception and spoofing attacks on networks of connected devices (Sebestyen; Popescu; Zmaranda, 2025).

Arduino Platform

Arduino, as shown in Figure 4, is an open-source electronic prototyping platform, widely recognized for its accessibility and versatility. Initially developed at the Ivrea Interaction Design Institute in Italy in 2005, the platform aims to facilitate the development of interactive and independent devices, even for those without prior experience in electronics or programming. The main feature of Arduino is its combination of open-source hardware and software, which allows users to create, modify, and share their own projects. Arduino boards are equipped with microcontrollers that can be programmed to read inputs, such as light from a sensor or the touch of a button, and generate outputs, such as activating a motor or lighting an LED. Programming is done using the Arduino language, based on Wiring, and the official IDE (Integrated Development Environment), based on Processing, facilitates writing and uploading code to the boards. (Arduino, 2025; Barrett, 2020). Arduino stands out for its ease of use, low cost, and large community, making it suitable for education, prototyping, and IoT applications. Its compatibility with sensors and actuators, and its support for shields, expand its functionality for developers and enthusiasts.

Figure 4 – Arduino UNO R3.



Source: Arduino, 2022.

3. METHODOLOGY

The methodology adopted in this study is applied in nature, with a qualitative approach, combining Design Science Research (DSR) for the design and evaluation of the artifact with pedagogical action research anchored in Problem-Based Learning (PBL), organized as a case study with a student team. DSR is appropriate for designing and validating technological artifacts in authentic contexts, while action research structures cycles of planning, intervention, and reflection in educational environments, and PBL provides a genuine problem that guides learning and investigation. This methodological arrangement has been indicated in recent studies that integrate technological development and pedagogical innovation in engineering and professional education (Goecks et al., 2021; Hoadley; Campos, 2022; Jensen; Dikilitas, 2025).

In terms of planning, the research was structured around two interconnected axes. On the pedagogical level, learning objectives, skills to be developed, roles of teachers and students, and formative assessment criteria were defined, in line with the principles of PBL, in which a real problem acts as a trigger for knowledge construction. On the technical level, the requirements of the artifact (an electronic module aimed at reducing energy waste in air conditioners), design constraints, interfaces with the physical environment, and performance metrics to be observed during in-use evaluation were specified. Based on this planning, the work was organized into linked stages. Initially, a review of the theoretical frameworks on PBL, DSR/DBR in engineering education, and automation solutions applied to energy efficiency was conducted, providing the basis for project decisions and research conduct. Next, the

pedagogical problem was modeled by formulating the challenge students would face, explaining the learning objectives, and defining rubrics and expected evidence, in line with design-based and action research approaches in technological education. Next, the artifact was engineered from a DSR perspective, including the ideation of the solution, the design of the electronic module for presence sensing and infrared signal emission, the definition of the hardware and software architecture, and the preparation of material lists and a preliminary risk analysis. This project culminated in progressive prototyping, which included the construction of a proof-of-concept in simulation and bench environments and, subsequently, the evolution to a functional prototype, in accordance with previously established acceptance criteria.

The evaluation in a realistic scenario was planned to verify compliance with technical requirements and, at the same time, generate data for analysis. Test parameters, procedures for using the module in a representative environment, temporal sampling strategies, and methods for recording variables of interest were defined. At the same time, the action research organized successive cycles of planning, execution, analysis, and reflection during orientation meetings, in which the team presented progress on the work, reviewed procedures, adjusted the project, and discussed the learning process itself in light of the proposed problem.

Finally, data from the use of the artifact (times, system responses, consistency of IR commands) and pedagogical evidence (reflective records, observations, intermediate productions) were planned for descriptive and interpretive analysis, to ensure traceability between design decisions, technical performance, and students' educational development. Recent methodological studies that articulate DSR, action research, and PBL provide support for this triangulation between artifact design, situated experimentation, and reflection on practice, lending rigor to the technical and educational contributions derived.

4. EXPERIMENTAL DEVELOPMENT

Electronic module

The ideation stage for the module's design stemmed from growing concerns about excessive electricity consumption in places where air conditioners remain on even when no one is present, such as classrooms. The goal was to develop an automated solution that reduces waste without compromising user comfort, integrating simple, low-cost technologies to create an intelligent air conditioner control system. The starting point was selecting a PIR (Passive

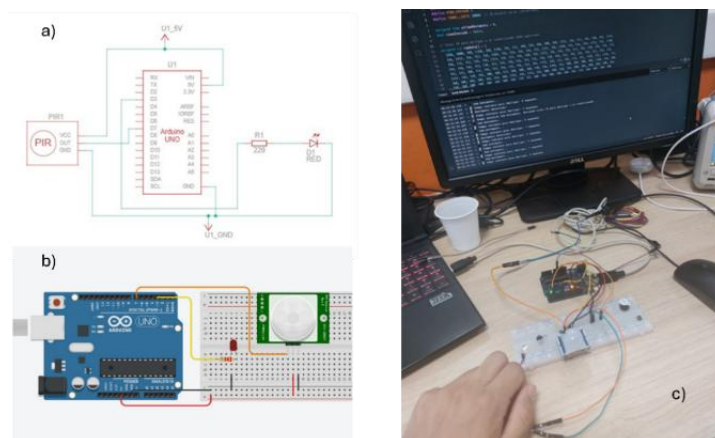
Infrared Sensor), widely used to accurately and cost-effectively detect human movement. The PIR sensor, integrated into a development board based on the ATmega328 microcontroller (Arduino Uno), detects movement and, in its absence, starts a configurable countdown to prevent the air conditioning from being abruptly or inconveniently turned off. This interval offers flexibility and prevents unwanted shutdowns during brief absences. Once the countdown is complete, the development board activates an infrared-emitting diode (IR LED) that transmits the coded signal for the air conditioner shutdown command. This signal simulates the device's original remote control, ensuring compatibility and operation without requiring modifications to the equipment.

Proof of Concept (PoC)

The proof of concept for the solution was based on motion detection using the HC-SR501 PIR sensor, an Arduino UNO R3 development board, and an infrared-emitting diode. A schematic diagram (Figure 5(a)) was prepared for subsequent simulation in Autodesk's Tinkercad virtual environment (Figure 5(b)) and for electronic assembly on a breadboard (Figure 5(c)), enabling the integration and testing of the electronic circuit.

The source code in C for the Arduino platform was based on a continuous monitoring cycle. Upon startup, the system enters a surveillance state, periodically checking for movement in the environment. Each time movement is detected, the timer is reset, keeping the air conditioner on until activity stops.

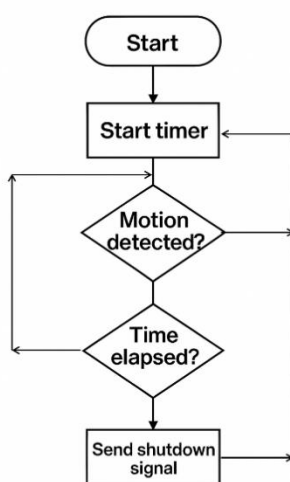
Figure 5 – Proof of Concept – (a) Schematic diagram, (b) Module simulation, (c) Electronic assembly



Source: The authors, 2025

Suppose the sensor does not register any movement during the programmable interval—set in the PoC code as 30 minutes—the microcontroller sends, via the IR LED, a coded signal compatible with the air conditioner remote control protocol, triggering its shutdown. It is important to note that even after sending the shutdown signal, the system continues to operate in monitoring mode. If a new movement is detected, the counter is reset, keeping the device in standby mode, as illustrated in the flowchart in Figure 6.

Figure 6 – Flowchart of operating logic



Source: The authors, 2025

To generate the IR signal correctly, a security vulnerability in the NEC protocol was exploited. Initially, the IR signal transmitted by the remote control of the air conditioners evaluated was intercepted by pressing the "off" button. The entire structure of the captured message—including the start bit, address bits, and command bits—was stored as shown in the code presented in Figure 7. Subsequently, this message is retransmitted to the air conditioner to turn it off after the time defined in the motion wait has elapsed. However, the air conditioner does not restart automatically: it requires human intervention using the device's original remote control. This design decision aims to reduce costs and complexity, avoid unnecessary on-off cycles, and ensure that restarts occur only when necessary. The code structure includes the use of specific libraries for time control and infrared signal emission, as well as digital reading routines for the PIR sensor and conditional logic for counter control.

Figure 7 – Infrared signal receiver code based on the NEC protocol

```
// Basic NEC decoding structure void decodeNEC() { if (detectLeaderPulse(9000, 4500)) {  
uint32_t data = 0; for (int i = 0; i < 32; i++) { if (pulseWidth() == 560) { if  
(spaceWidth() > 1000) { data |= (1 << i); // Logic '1' } else { // Logic '0' - bit already  
0 } } } // Validate and extract address/command uint8_t address = data & 0xFF; uint8_t  
command = (data >> 16) & 0xFF; } }
```

Source: The authors, 2025

The proof of concept underwent functional and acceptance testing in a controlled environment, verifying compliance with technical requirements, including presence detection, response time, and correct infrared signal emission. The tests were carried out in a 3 x 4 meter meeting room equipped with an Agratto Split Hi Wall LIV Top Inverter 24,000 BTU/h air conditioner, model LCST24QF-02I. The PoC was positioned on the central table in the room, pointed at the evaporator unit at approximately 3 meters, and the source code embedded in the Arduino board was programmed to turn off the air conditioner after 30 minutes of inactivity.

During the testing phase, twenty consecutive sessions were conducted, all of which were successful. In each session, the system correctly identified the absence or presence of movement, took the necessary actions, and shut down the equipment according to the scheduled time, with a maximum variation of 0.008 minutes—equivalent to 0.5 seconds, as shown in Table 1, clearly demonstrating the technical feasibility of the solution and confirming the effectiveness of the integration between the electronic components and the embedded control logic.

Table 1: PoC functional testing routine

Test No.	Moviment				Has the timer been reset?	Estimated shutdown time (min)	Real time to shutdown (min)
	-	10 min	20 min	29 min			
1	X	-	-	-	yes	30	30.006 min
2	X	-	-	-	yes	30	30.006 min
3	X	-	-	-	yes	30	30.008 min
4	X	-	-	-	yes	30	30.006 min
5	X	-	-	-	yes	30	30.008 min
6		X	-	-	yes	40	40.008 min
7		X	-	-	yes	40	40.005 min
8		X	-	-	yes	40	40.005 min
9		X	-	-	yes	40	40.006 min
10		X	-	-	yes	40	40.006 min
11	-	-	X	-	yes	50	50.006 min
12	-	-	X	-	yes	50	50.006 min
13	-	-	X	-	yes	50	50.008 min
14	-	-	X	-	yes	50	50.006 min
15	-	-	X	-	yes	50	50.008 min
16	-	-	-	X	yes	59	59.006 min
17	-	-	-	X	yes	59	59.006 min
18	-	-	-	X	yes	59	59.006 min
19	-	-	-	X	yes	59	59.008 min
20	-	-	-	X	yes	59	59.008 min

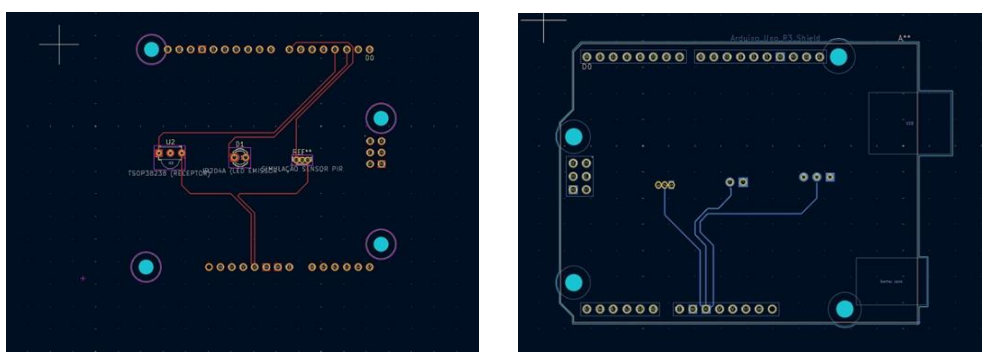
Source: The authors, 2025.

Prototype development

Based on the PoC, the final printed circuit board (PCB) of the electronic module was designed in KiCad. This free EDA suite integrates schematic capture, PCB layout, Gerber visualization, and manufacturing file generation. The use of KiCad enabled the consolidation of the electrical schematic, the association of footprints, the definition of net classes and design rules (DRC) appropriate for a single-sided PCB (copper on one side), with ground flood and tracks sized for the system's current levels. The tool selection took into account the extensive official documentation and ecosystem maintained by the KiCad project.

After validation of the DRC, the manufacturing files (Gerber and drilling/Excellon) were exported for subtractive production by milling (isolation milling), a method suitable for rapid prototyping in the laboratory, as it does not require chemical baths, as shown in Figure 8. The PCI was manufactured using a virgin, single-sided copper-clad board, machined on a TTP PCB-Proto 1S prototyping machine. This equipment performs automated milling of the tracks and drilling. Typical specifications released by university fablabs indicate hole diameters ranging from 0.3 mm to 2.5 mm and speeds suitable for agile prototyping.

Figure 8 – Printed Circuit Board made in KiCad. On the left side, top view. On the right side, bottom view



Source: The authors, 2025.

Once machining was complete, finishing was carried out (removal of burrs, cleaning, and visual inspection), followed by continuity tests. Next, the busbars, connectors, and PIR module were assembled on the PCI (Figure 9), and a new electrical inspection and power-on test were performed to verify polarities, voltage levels, and track integrity. The assembly was then integrated into the final prototype of the module, preserving compatibility with the IR emitter and embedded logic described in the PoC.

Figure 9 – Prototype of the PCB attached to the Arduino UNO R3



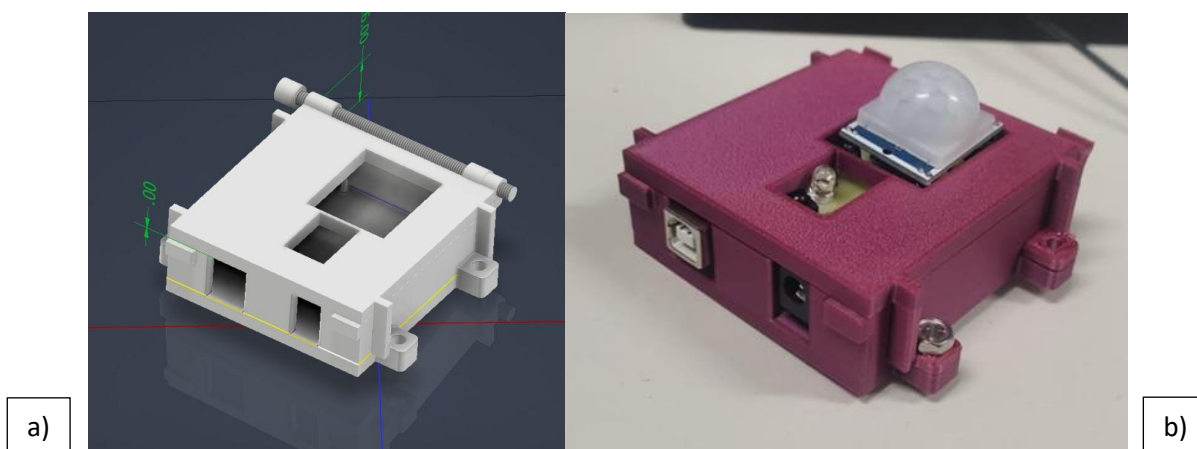
Source: The authors, 2025.

Cabinet development

The mechanical cabinet was developed in Autodesk Inventor, a 3D CAD software for parametric modeling of mechanical components and assemblies, widely used in engineering projects to validate shape, fit, and function before physical manufacturing. The casing was modeled based on the dimensions of the final PCI, the PIR module, and the power and signal connectors, establishing geometric constraints to ensure adequate clearances and alignment of the mounting points. Construction elements such as wall thickness, screw holes, chamfers, and roundings were also defined, as were specific openings for the PIR sensor's field of view and for the IR LED's infrared beam, preserving the functionality of the presence detection system and the remote control of the air conditioner. The cabinet was designed in two main parts—base and cover—coupled by mechanical fastening, facilitating both the assembly of the electronics and future maintenance. The external geometry was designed for installation in air-conditioned indoor environments, seeking a compact format, as illustrated in Figure 10.

From the final 3D model, the appropriate export files for additive manufacturing were generated in a format compatible with the 3D printer's slicer. The cabinet was manufactured using a P1-series printer from Bambu Lab, a company specializing in desktop 3D printers for personal, educational, and professional use. PLA (polylactic acid) filament was chosen, a thermoplastic widely used in fused deposition modeling (FDM) technology due to its low shrinkage, good layer adhesion, and ease of printing, in addition to being produced from renewable sources, such as corn starch derivatives. The printing parameters (layer height, infill, number of perimeters, and extrusion temperature) were adjusted to ensure sufficient rigidity to protect the electronics while maintaining a manufacturing time compatible with use in a laboratory environment. After printing, the parts were cleaned and surface-finished, then assembled with the electronic prototype, resulting in a compact, protected module ready for installation in a real environment.

Figure 10 – (a) 3D model of the enclosure for the PCB and Arduino, developed using the Inventor 1.0 platform. (b) Printed enclosure with hardware installed



Source: The authors, 2025.

Assessment in a Real Environment

The evaluation in a real environment was carried out in a classroom equipped with a Carrier Floor-Ceiling 48,000 BTU/h air conditioner, with a nominal electrical power of 14,068 W (Procel Table). The equipment typically operates from 8 a.m. to 10 p.m. (14 hours/day), Monday through Friday (5 days/week), totaling approximately 3,640 hours/year. The prototype was permanently installed, with a direct line of sight to the evaporator unit and adequate coverage of the occupied area by the PIR sensor.

Before activating the module, the air conditioner's energy consumption was measured under conventional use conditions, using portable energy analysis instrumentation (power and energy in kWh), with photographic records of the installation and readings (Figure 11). The procedure was then repeated with the prototype in operation, maintaining the same usage pattern (schedules, setpoint, and occupancy profile). The data from the two scenarios were organized and processed in the energy audit spreadsheets of the Energy Efficiency Network in Public Buildings (RedEE), allowing the reduction in consumption to be quantified.

Figure 11 – Field data collection using an energy analyzer



Source: The authors, 2025.

4. RESULTS AND DISCUSSION

Field tests with the electronic module, applied to a Carrier Floor-Ceiling air conditioner with a capacity of 48,000 BTU/h (14.068 kW, 3,640 h/year regime), resulted in an estimated annual consumption of 51,207.52 kWh/year without the prototype and 45,369.86 kWh/year with the prototype, which corresponds to a saving of 5,837.66 kWh/year, or 11.4%. These values are in line with results reported for occupancy-based HVAC controls in real buildings, which typically show reductions of 5–20% in air conditioning energy when operation is based on actual user presence. Recent studies of non-invasive control of air conditioners, based on presence sensors and remote control, also report significant savings, often exceeding 30–40% in experimental scenarios, reinforcing the reasonableness of reductions of around 10% under more realistic and conservative conditions of use (Harahap *et al.*, 2025).

CO₂ equivalent emissions can also be estimated using an emission factor of 28.9 g CO₂/kWh (0.0289 kg CO₂/kWh) for electricity from the SIN in 2025, based on monthly figures released by MCTI/SIRENE for April 2025 (MCTI, 2025). The analyzed air conditioner emits approximately 1,479.9 kg CO₂/year without the prototype and 1,311.2 kg CO₂/year with the prototype, resulting in a mitigation of approximately 168.7 kg CO₂/year per unit. This result is consistent with the order of magnitude of emission reductions reported in studies on retrofitting and HVAC control in public and institutional buildings, which indicate significant reductions in carbon footprints from low-cost efficiency measures (Sharma *et al.*, 2024).

When the analysis is extrapolated to Block C, with 35 air conditioners conservatively assumed to be 48,000 BTU/h units operating under the same regime, total annual consumption rises to 1,792.263.2 kWh/year ($\approx$ 1.79 GWh/year) without the prototype to 1,587,945.2 kWh/year ($\approx$ 1.59 GWh/year) with the prototype, resulting in savings of approximately 204,318.0 kWh/year ($\approx$ 204 MWh/year). The associated emissions fall from about 51,796.4 kg CO₂/year ($\approx$ 51.8 tCO₂/year) to 45,891.6 kg CO₂/year ($\approx$ 45.9 tCO₂/year), with annual mitigation of around 5.9 tCO₂/year in this block alone.

From an economic standpoint, even though the actual tariff class for the campus is A4 (Blue/Green tariff), using Amazonas Energia's conventional residential B1 tariff in 2025, at R\$0.707/kWh, as a simplified reference, illustrates the magnitude of the benefits. For a single air conditioner, the estimated annual cost falls from R\$36,203.72 to R\$32,076.49, with savings of approximately R\$4,127.22/year. For the set of 35 units in Block C, the estimated annual expense varies from R\$1,267,130.08 to R\$1,122,677.25, resulting in savings of approximately R\$144,452.83/year. These values are consistent with recent analyses indicating a favorable cost-benefit ratio for HVAC control strategies based on occupancy and lighting automation, especially in educational and service buildings in hot climates, where air conditioning accounts for a significant portion of electricity consumption (PNNL, 2023).

5. FINAL REMARKS

The study presented the complete development of a low-cost electronic module based on an Arduino for the automatic shutdown of air conditioners via PIR sensor absence detection and IR commands compatible with the original remote control. The prototype, housed in a dedicated 3D-printed case, proved technically feasible, easy to install, and non-invasive, preserving the manual operation of the equipment. In real-world testing with a 48,000 BTU/h (14.068 kW, 3,640 h/year) Carrier Floor-Ceiling air conditioner, the module reduced estimated annual consumption by 11.4%, from 51.2 MWh/year to 45.4 MWh/year, consistent with the 5–20% savings range reported for occupancy-based HVAC control strategies in real buildings. With an emission factor of 28.9 g CO₂/kWh for the SIN in 2025, this translates into approximately 0.17 tCO₂/year per unit. When extrapolated conservatively to the 35 devices in Block C, the savings reach approximately 204 MWh/year, and the reduction in emissions reaches 5.9 tCO₂/year, indicating a significant impact on energy and the environment for a single block of the building.

Even using the residential B1 tariff (R\$0.707/kWh) as a simplified reference, the estimated savings are around R\$4,100/year per device and R\$144,000/year for Block C, illustrating the strong potential for economic return from a simple, low-investment intervention. These results are consistent with recent studies that highlight occupancy-oriented control and light automation as highly cost-effective strategies in educational and service buildings in hot climates.

Despite the simplifications adopted (nominal power, typical operating regime, and conservative extrapolations), the results indicate that the Arduino-Based Electronic Module for Air Conditioning System Optimization is a promising solution for reducing consumption, operating costs, and CO₂ emissions in public buildings. Future work may refine consumption and emissions models, incorporate continuous monitoring, integrate the module into building energy management platforms or DERMS, and systematically evaluate the impact on thermal comfort and user acceptance, especially in critical contexts such as the Amazon.

6. CONFLICTS OF INTEREST

The authors declare that there are no competing financial interests or known personal relationships that could have influenced the inferences reported in this article.

6. REFERENCES

ANEEL. **A transição energética no Brasil**. [S. l.], 2025. Available at: <https://www.gov.br/aneel/pt-br/assuntos/transicao-energetica/a-transicao-energetica-no-brasil>. Access at: 25 ago. 2025.

ARDUINO. **Arduino - Home**. [S. l.], 2025. Available at: <https://www.arduino.cc/>. Access at: 25 ago. 2025.

BARRETT, Steven F. Arduino Platforms. In: BARRETT, Steven F. (org.). **Arduino I: Getting Started**. Cham: Springer International Publishing, 2020. p. 33–73. Available at: https://doi.org/10.1007/978-3-031-79915-0_2. Access at: 25 ago. 2025.

BELAÏD, Fateh. The limits of energy conservation: Why doubling current energy efficiency progress is no easy feat. **Energy Research & Social Science**, [s. l.], v. 127, p. 104253, 2025.

CHEN, Yujiao; YIN, Rongxin. **Estimating electricity saving-potential in small offices using adaptive thermal comfort**. [S. l.]: arXiv, 2022. Available at: <http://arxiv.org/abs/2205.10324>. Access at: 19 ago. 2025.

GEWEDA, A. E. et al. Mitigating CO2 emissions: A review on emerging technologies/strategies for CO2 capture. **Journal of the Energy Institute**, [s. l.], v. 118, p. 101911, 2025.

GOECKS, Lucas Schmidt et al. Design Science Research in practice: review of applications in Industrial Engineering. **Gestão & Produção**, [s. l.], v. 28, p. e5811, 2021.

GUINThER, Jorge Luís Nunes. A APLICAÇÃO DE UM SENSOR ELÉTRICO DE MOVIMENTO E PRESENÇA EM PROCEDIMENTOS DE AUTOMAÇÃO INDUSTRIAL. [s. l.], 2018.

HARAHAP, Nurmahendra et al. Reduction Of Air Conditioner Energy Consumption Through The Implementation Of A Non-Invasive Sensor Based Automatic Control System. **International Journal of Science and Environment (IJSE)**, [s. l.], v. 5, n. 3, p. 87–94, 2025.

HOADLEY, Christopher; CAMPOS, Fabio C. Design-based research: What it is and why it matters to studying online learning. **Educational Psychologist**, [s. l.], v. 57, n. 3, p. 207–220, 2022.

IDE, Tobias. Recession and fossil fuel dependence undermine climate policy commitments. **Environmental Research Communications**, [s. l.], v. 2, n. 10, p. 101002, 2020.

JENSEN, Ida Bruheim; DIKILITAS, Kenan. A scoping review of action research in higher education: implications for research-based teaching. **Teaching in Higher Education**, [s. l.], v. 30, n. 1, p. 84–101, 2025.

KIM, Minchul; SUH, Taeweon. Eavesdropping Vulnerability and Countermeasure in Infrared Communication for IoT Devices. **Sensors (Basel, Switzerland)**, [s. l.], v. 21, n. 24, p. 8207, 2021.

MCTI, em 12/06/2025. **MCTI publica fatores de emissão de CO2 da geração de energia elétrica no Brasil para 2025.** [S. l.], 2025. Available at: <https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2025/06/mcti-publica-fatores-de-emissao-de-co2-da-geracao-de-energia-eletrica-no-brasil-para-2025>. Access at: 10 nov. 2025.

MERABET, Ghezlane Halhoul *et al.* **Intelligent Building Control Systems for Thermal Comfort and Energy-Efficiency: A Systematic Review of Artificial Intelligence-Assisted Techniques.** [S. l.]: arXiv, 2021. Available at: <http://arxiv.org/abs/2104.02214>. Access at: 19 ago. 2025.

OLIVEIRA, Lucas Leonardo Silva. Inclusão de Um Sensor de Detecção de Movimento no Android Open Source Project (AOSP) de Forma Nativa Para Uso em Sistema de Segurança. [s. l.], 2025.

ORTIZ-PEÑA, Aarón; HONRUBIA-ESCRIBANO, Andrés; GÓMEZ-LÁZARO, Emilio. Electricity Consumption and Efficiency Measures in Public Buildings: A Comprehensive Review. **Energies**, [s. l.], v. 18, n. 3, p. 609, 2025.

PIR. **Sensor de movimento PIR HC-SR501: Especificações, folha de dados e configuração de pinos.** [S. l.], 2025. Available at: <https://www.ariat-tech.pt/blog/HC-SR501-PIR-motion-sensor-specifications-datasheet-and-pin-configuration.html>. Access at: 19 ago. 2025.

PNNL. **Adopting Occupancy-Based HVAC Controls in Commercial Building Energy Codes: Analysis of Cost-Effectiveness and Decarbonization Potential.** [S. l.], 2023. Available at: <https://www.pnnl.gov/publications/adopting-occupancy-based-hvac-controls-commercial-building-energy-codes-analysis-cost>. Access at: 10 nov. 2025.

REDEE. **RedEE Edifícios Públicos.** [S. l.], 2025. Available at: <https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/sef/redee>. Access at: 13 nov. 2025.

SEBESTYEN, Hannelore; POPESCU, Daniela Elena; ZMARANDA, Rodica Doina. A Literature Review on Security in the Internet of Things: Identifying and Analysing Critical Categories. **Computers**, [s. l.], v. 14, n. 2, p. 61, 2025.

SHARMA, Renu *et al.* Energy efficiency retrofitting measures of an institutional building: A case study in eastern India. **Cleaner Energy Systems**, [s. l.], v. 7, p. 100111, 2024.