A low-budget mathematically scalable sensor solution to reduce energy consumption in buildings.

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Abstract

Reducing the consumption of electrical equipment such as air conditioning and lighting in buildings is a challenge around the world. Sensor-based control systems supported by intelligent, adaptive mathematical algorithms can control electrical equipment optimally to save energy and maintain user satisfaction. The system combines PIR sensors, low-consumption temperature and lighting sensors that analyze the characteristics of the environment and allow efficient control decisions to be made in electrical equipment such as air conditioning and lighting system present in the building. This paper presents the design and implementation of the proposed system in a real room and the analysis of the system implementation in a simulation for a building. The simulations of total energy consumption during a period of one year of an occupied building were carried out to verify the performance and energy saving in some scenarios of climatic conditions. The proposed system reduces total energy consumption by 10%.

Keywords: wireless sensor networks, power management, energy efficiency.

I. INTRODUCTION

Energy efficiency in Latin American countries is a challenge and a long-term goal to achieve according to CEPAL, as detailed in [1]. Although there are sectors (such as industry) where energy savings are more noticeable, it is possible to implement these strategies in a house, a building, an office, among many other scenarios; the more environments that can be included, the energy consumption will be much lower. According to ECLAC reports, certain programs and policies are carried out in Ecuador to improve energy efficiency, such as: Renova Refrigeradores Program and the Energy Efficiency Plan for cooking and water heating. However, there is no policy to improve energy efficiency in lighting or air conditioning systems, since it is not considered a high consumption sector, such as transportation systems and industry, as explained in [2].

Under this premise, this paper presents the design of a space occupancy measurement system for control of energy consumption in a workspace. The system is based on the use of occupancy and vacancy sensors and environmental variables meters. In this way, it seeks to monitor the use of devices connected to the system.

The objectives to be achieved in this project respond to the proposal of a solution for the reduction of energy consumption of electrical equipment in buildings, through the study of people counting technologies and the design of a system for this purpose. From this information, it is possible to define the behavior of electrical equipment in this space, and provide a solution to optimize the use of electricity.

Based on the information collected by low-cost sensors that analyze the temperature and illumination of a room, which are environmental variables of the area, and the occupancy of the place, it is possible to obtain certain data that, after going through various mathematical methods that allow converting these values into useful information, will be useful for the automatic control of the devices that make up the air conditioning and lighting systems.

This document is structured as described below: Section II presents the analysis of technologies for estimating the occupancy of a system, and shows which one is the optimal technology for the system to be developed. Section III develops the system (hardware and software) for people counting to implement and its application in energy monitoring. Section IV shows the establishment of operating and control thresholds of the devices that make up the air conditioning and lighting systems, finally, in section V, present the results of the system, together with the simulations performed.

II. LITERATURE ANALYSIS

This section shows the four main technologies analyzed for the development of the electronic people counting and control system for air conditioning and lighting devices.

A. Open Computer Vision (OpenCV)

OpenCV, as described in [3], is an open source computer vision library, which allows the counting and tracking of people through an algorithm based on centroids analysis. In [4] it is shown that, by delimiting a person, establishing his location on a plane and analyzing the Euclidean distance of the person when he is moving, it is possible to identify the direction of the person, and the number of people that are interacting in that moment in that defined space.

B. Passive Infrared Sensor (PIR)

The PIR sensor is a device that detects and measures infrared radiation to analyze whether there is movement in the area it is analyzing. This sensor does not emit any type of radiation (hence its name of passive), but rather analyzes the radiation already existing in the environment and detects disturbances, as explained in [5]. Although this technology can be used as a complement to more robust systems, such as video surveillance systems, as observed in

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[6], the idea of using it as the main detection system for people is not ruled out.

C. Analysis of WiFi signal disturbances

As discussed in [7], it is possible to develop a people counting system by using a receiver and a transmitter of Wi-Fi signals at two defined points, knowing that the passage of people between these devices generates disturbances between the signals received and transmitted. By means of the received signal intensity indicator and an algorithm based on the Kullback-Leibler divergence, it is possible to know the estimated number of people in the studied area.

D. Sensors of environmental variables

Certain characteristics of the studied area, such as temperature, lighting, $CO2$, among others, provide information not only on the occupation or vacancy of a room, but also on the environment within it, data that would allow the air conditioning systems to and lighting are in operation according to the needs of the room at a given time, as discussed in [8].

III. ELECTRONIC SYSTEM DESIGN

The system designed for this project can be divided into two main parts: mathematical design and hardware and programming design.

A. Mathematical design

The mathematical design of the system is based on the work of [9], which carried out the implementation of two PIR sensors in each door of each room on a floor of a building. The distribution of sensors is shown in figure 1, and equation (1) shows the analysis of the entrance and exit sensors (i and j respectively), where the action of entering or leaving a room must be carried out in an equal time or less than Δt which for this project was defined in 3s.

$$S_{i,j} = \{\, x_i(t_c), x_j(|t - t_c| \leq \Delta t) \,\} \quad (1)$$

To know the number of people in the room at a given time, it is necessary to add the content of the matrix shown in equation (2), which stores the values of the interactions in equation (1), knowing that when a person enters to the room, a value of +1 is stored, and when a person leaves, a value of -1 is stored.

$$S = \{\, x_i(t_i),\ x_{i+1}(t_{i+1}),\ x_{i+2}(t_{i+2}), \dots, x_n(t_n)\} \quad (2)$$

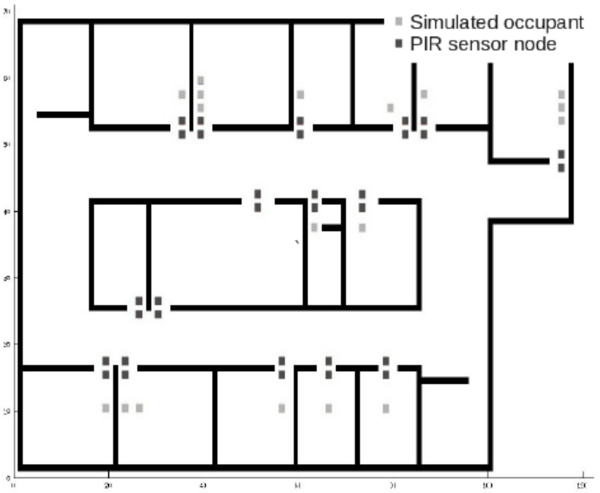

Figure 1. Initial state of the people counting experiment using PIR sensors. Adapted from Wahl et al., 2012.

B. Hardware and Programming design

The hardware used for the development of the system is composed of the HC-SR501 PIR sensor and a Raspberry Pi 4 Model B. Two sensors were used, one outside the room and the other inside, both connected to the Raspberry that analyzes the signals sent by them. It is possible to use the HC-SR501 sensor autonomously, that is, it does not need external hardware such as the Raspberry for its operation, but its use is recommended not only for powering the sensor, but also for storing the counting data of the room, for further analysis. Figure 2 shows the flowchart of the system's operation with the two sensors implemented, and figure 3 shows the connection of the sensors to the Raspberry.

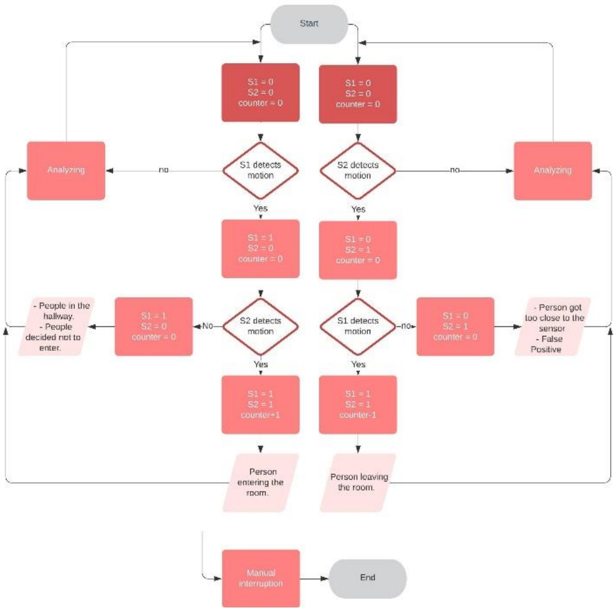

Figure 2. Flowchart of electronic people counting system using PIR sensors. Source: Author.

Figure 3. PIR sensors connected to Raspberry Pi 4. Source: Author.

IV. ANALYSIS OF ENVIROMENTAL VARIABLES

In order to analyze the environmental characteristics of the monitored room, sensors were used to analyze the temperature and lighting of the place. This, combined with the presence or vacancy status of people in the area, allow obtaining information that the air conditioning and lighting systems use to improve their energy consumption.

A. Performance standards

In order for the air conditioning and lighting systems to operate under the same parameters and to provide thermal and lighting comfort to people, several documents have been analyzed which describe the optimum temperature and lighting for office work, which are described in table 1 and 2.

Table 1. Recommended temperature levels in offices. Adapted from NTP 501, Calleja, 1998.

TYPE OF WORK	**OPTIMAL TEMPERATURE (in °C)**	**HUMIDITY LEVEL**	**AIR SPEED (in m/s)**
Intellectual work in seated position	18º to 24º	40% to 70%	0.1
Work in standing position	17º to 22º	40% to 70%	0.1 to 0.2
Hard work	15º a 21º	30% to 65%	0.4 to 0.5
Very hard work	12º to 18º	20% to 60%	1.0 to 1.5

Table 2. Recommended lighting levels in offices. Adapted from ISO 8995 - 2002 standard.

TYPE OF ACTIVITY PERFORMED	**LIGHTING MAINTAINED (*E*m) in lx**
Archiving, copying, circulation.	300
Writing, typing, reading, data processing.	500
Technical Drawing	750
CAD workstation	500
Conference and meeting room	500
Reception bureau	300
Archives	200

B. Temperature monitoring system

The room's thermal measurement system used a DS18B20 sensor and the Raspberry Pi 4 mentioned in the previous section. The program was designed in Python 3, using the w1thermsensor library, thanks to the 1-Wire protocol used by the sensor, which allows data to be sent to the Raspberry using a single physical communication pin. Figure 4 shows the flowchart of the data receiving and sending process.

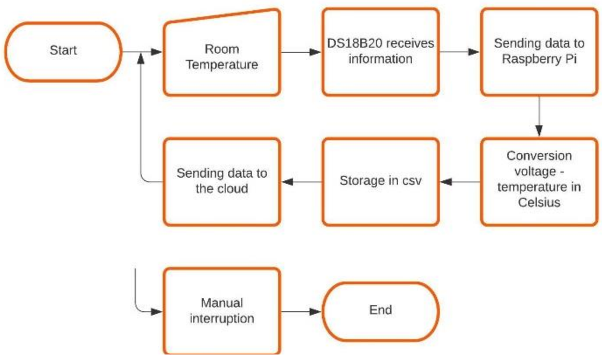

Figure 4. Flowchart of the electronic temperature monitoring system using the DS18B20 sensor. Source: Author.

The values obtained for temperature and lighting in the room were stored in a csv file for mathematical processing, which will be discussed later.

C. Lighting monitoring system

The system that monitored the lighting in the room is composed of a BH1750 sensor and the Raspberry Pi 4. The program was designed in Python 3 using the smbus library. The sensor operates using the I2C protocol, which requires two physical pins for communication. The temperature and lighting sensors receive a 3.3V power supply from the Raspberry and the analysis of the variables is carried out every 2 minutes continuously, thanks to the crontab tool. In this way, by not continuously analyzing the room, the sensors can be kept in a low power consumption state when the information is not required. Figure 5 shows the flowchart of the process for obtaining lighting information, and Figure 6, the physical connection of sensors to the Raspberry Pi 4.

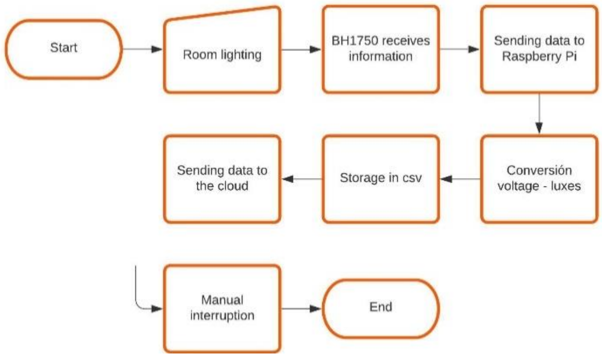

Figure 5. Flowchart of the electronic lighting monitoring system using the BH1750 sensor. Source: Author.

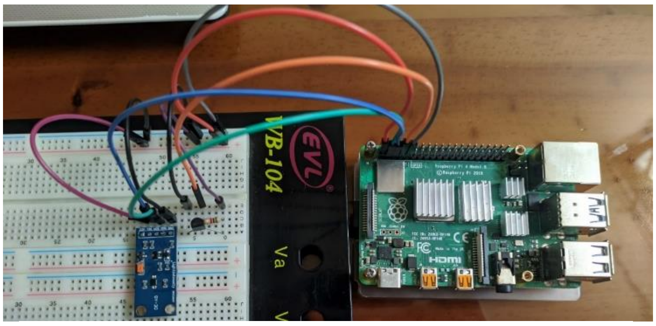

Figure 6. DB18B20 and BH1750 sensors connected to the Raspberry Pi 4. Source: Author.

D. Sensors of environmental variables

The experimental data obtained through the sensors were processed using mathematical modeling techniques (least squares) and grouping algorithms (K Means), in order to know the behavior of these variables and improve the accuracy of the data that will serve to control the air conditioning and lighting systems.

The least squares technique allows obtaining a polynomial equation based on experimental data, looking for the best possible fit (defined by the user) to the information to be modeled. In [10] the procedure to follow when using this method is detailed, whose main objective, after having defined the degree of the equation, is to find the coefficients corresponding to the independent variable. The equation obtained will have a level of error depending on the degree chosen; the lower the degree, the greater the error in the equation.

The K Means clustering algorithm differentiates elements of a group of data according to their characteristics, and define an average value to represent. This is done by measuring Euclidean distances and defining a number of clusters, which will be the number of sets into which the data will be divided. The work of [11] shows that, in order to correctly define the number of clusters that the data require, techniques such as the "Jambú elbow" can be applied, in order to find the point where there are no noticeable changes between the sets already defined.

Thanks to the numpy and sklearn.cluster Python libraries, it is possible to process the sensor data stored in csv format directly from the Raspberry Pi. Through these techniques it will be possible to define the temperature and lighting level in the room with greater accuracy, in addition to contributing to the establishment of operating thresholds for air conditioning and lighting devices.

V. RESULTS OBTAINED

To corroborate the operation of the system, experimental tests and energy consumption simulations were carried out.

A. Results of the people counting system

The two PIR sensors were installed in a room in a residential building. Two hundred experiments were carried out, half oriented to the entrance to the room and the others, to the exit. Table 3 shows the results obtained, where the use of the HC-SR501 sensor obtains an average accuracy level of about 80%. Considering that the sensor used is one of the cheapest on the market and that high precision is not required to meet the objectives of this project, the use of this sensor is ideal.

Table 3. Results obtained from the people counting system using PIR sensors. Source: Author.

ACTION	PERCENTAGE
Entry to the room	84%
Exit from room	74%
False positives	10%
Average level of accuracy	79%

B. Results of the lighting monitoring system

The lighting values in the room were obtained experimentally in four days, placing the BH1750 sensor in different places each day; the same procedure was carried out for temperature measurement. The behavior of the lighting in the room is reflected in figure 7, in addition to the cubic equation generated by the least squares technique, which models the behavior of this variable to send more precise data to the lighting device control system.

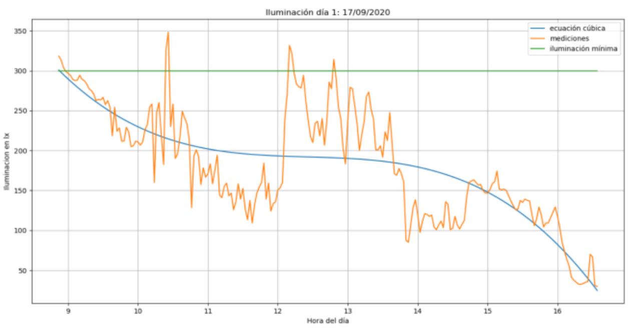

Figure 7. Graph of lighting behavior in the room with respect to the mathematically calculated values. Source: Author.

Equations (3), (4), (5) and (6) show the behavior of the room lighting in the working area, the most illuminated area, the least illuminated area and the center of the room, respectively. The graph shown in figure 7 corresponds to the values in the work zone. The units of the results are displayed in lux, a measure of lighting with respect to the area in m2 of the room.

$$-2.211x^3 + 82.43x^2 - 1027x + 4467 \quad (3)$$

$$0.6903x^3 - 31.12x^2 + 445.6x - 1962 \quad (4)$$

$$9.903x^3 - 471.8x^2 + 6926x - 28997.67 \quad (5)$$

$$-9.757x^3 - 366.9x^2 + 4552x - 19677.02 \quad (6)$$

For the analysis of the lighting data using the K Means clustering technique, it was expected to obtain a differentiation of lighting information with respect to the time of day, as will be observed later in the clustering of temperature data. However, since there is a great dispersion between the data obtained (because the information obtained was from natural light), the information of the clusters generated as seen in figure 8 is not useful for the purposes of this analysis.

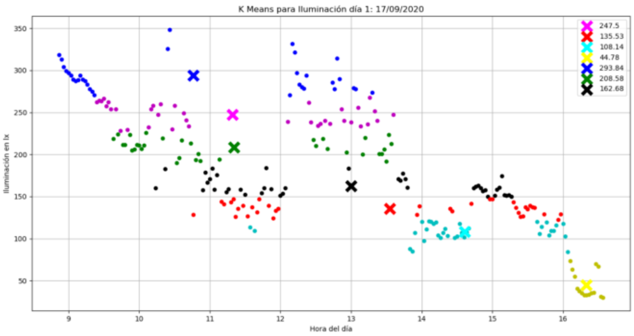

Figure 8. Clustering analysis of room lighting using K Means. Source: Author.

C. Results of the temperature monitoring system

The temperature values in the room were obtained experimentally in four days, following the same process explained for lighting monitoring, in this case using the DS18B20 sensor. Figure 9 shows the results obtained in the room, together with the graph of the cubic equation generated by least squares.

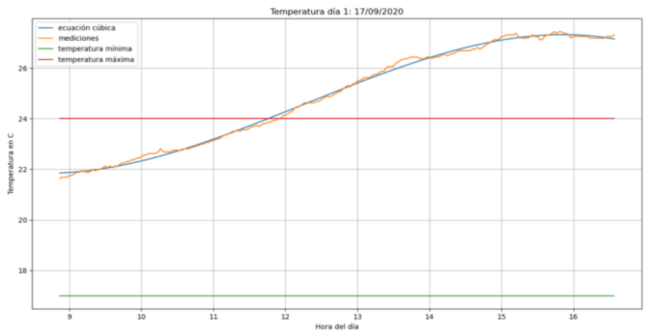

Figure 9. Graph of room temperature behavior with respect to mathematically calculated values. Source: Author.

Equations (7), (8), (9) and (10) show the behavior of the temperature in the room, in the same areas described for the previous lighting equations. Figure 9 shows the temperature values in the working area. Results units are displayed in Celsius.

$$-0.02967x^3 + 1.092x^2 - 12.25x + 65.31 \quad (7)$$

$$-0.01268x^3 + 0.4995x^2 - 6.018x + 44.13 \quad (8)$$

$$-0.004903x^3 + 0.1637x^2 - 1.3x + 23.5 \quad (9)$$

$$-0.008017x^3 + 0.285x^2 - 2.825x + 28.65 \qquad (10)$$

In addition to the least squares analysis, the use of the K Means algorithm is proposed, in order to know the average temperature values that will be sent to the temperature device control system in a period of time. It is observed in figure 10 that the variation between experimental values and those calculated mathematically is reduced for this variable, contrary to what happens with the lighting data, for which the clustering analysis is effective only for the temperature values of the room.

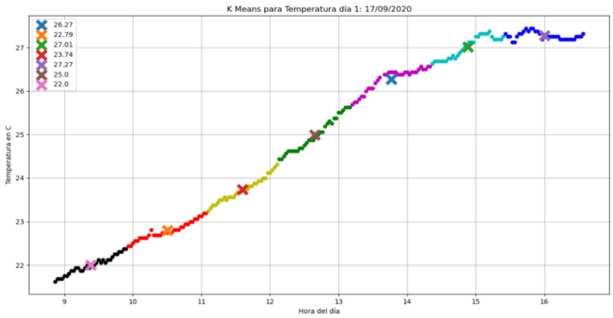

Figure 10. Clustering analysis of room temperature using K Means. Source: Author.

Once the clusters per working hour of the temperature data have been obtained, it is possible to perform the same procedure for the data mathematically calculated by means of least squares, as shown in table 4. Through this, an average value can be obtained between the two sources of information, which will be the data sent to the air conditioning control system to make decisions for its operation.

Table 4. Comparison between experimental and mathematically calculated clusters. Source: Author.

# Clúster (time of day)	Experimental Clusters	Clusters from equation	Average
1 (9–10 am)	22.00	22.05	22.03
2 (10–11 am)	22.79	22.81	22.80
3 (11 am–12 pm)	23.74	23.87	23.81
4 (12–13 pm)	25.02	25.01	25.02
5 (13–14 pm)	26.29	26.11	26.20
6 (14–15 pm)	27.02	26.97	27.00
7 (15–16 pm)	27.27	27.27	27.27

D. Sensors of environmental variables

In order to verify the effectiveness of energy saving through the implementation of this system, a simulation was developed using the OpenStudio program, software based on EnergyPlus, to analyze the consumption patterns of a building and observe the percentage of reduction in energy consumption implemented improvements in air conditioning and lighting systems.

Three simulations were carried out, the first with typical electrical energy consumption values, given by the ANSI/ASHRAE 189.1-2009 standard, as detailed in [12]. The second applies improvements to lighting systems, and the third applies improvements to air conditioning and lighting systems.

The improvements were applied in the "Hours" tab, where you can modify the times and operating values of lighting and air conditioning in the rooms of a building. Thanks to the information obtained by the environmental sensors, it is possible to know the state of the room in a period of time and define the moments in which these devices must operate. The operating levels are defined by the mathematical values discussed in the previous section, so that each device knows how to operate in response to the state of the current environment.

Table 5 shows the level of energy consumption of a building without the application of any improvement in energy consumption, and in contrast, the values of energy consumption with improvements implemented are shown in table 6. The level of savings is 9.95% compared to the building without improvements, which demonstrates the effectiveness of the designed system, even though OpenStudio cannot model the people counting system. If the occupancy level of the room was considered, the energy savings would be even greater.

Table 5. Results obtained from the simulation of energy consumption of a building without implementation of improvements. Source: Author.

Parameters	Value
Total net building area	132 m^2
Total annual energy consumption	5247 kWh
Energy consumption per m^2	39.66 kWh/m^2
Heating energy consumption	611 kWh
Cooling energy consumption	1783 kWh
Lightning energy consumption	1081 kWh
Energy consumption for electronic devices	1772 kWh

Table 6. Results obtained from the simulation of energy consumption of a building with implementation of improvements. Source: Author.

Parameters	Value
Total net building area	132 m^2
Total annual energy consumption	4725 kWh
Energy consumption per m^2	35.71 kWh/m^2
Heating energy consumption	742 kWh
Cooling energy consumption	1450 kWh
Lightning energy consumption	761 kWh
Energy consumption for electronic devices	1772 kWh

VI. CONCLUSIONS

Thanks to the results of the mathematical processing of the environmental variables data and the simulation performed in OpenStudio, it can be determined that the main objective of this work, defined as the reduction of energy consumption in an office, which was the case study used in the simulation, by 10%, was achieved. This model can be replicated in various scenarios, such as homes, hotels, restaurants, among others.

The development of the people counting system explained in this paper allows to know the occupation or vacancy of a room, in order to determine whether the air conditioning and lighting systems should operate or not. If required, the devices will operate based on operating standards, to maintain thermal and lighting comfort, and based on information from the environment captured by environmental variables sensors, to reduce unnecessary energy consumption.

The mathematical processing used in the experimental data makes it possible to provide a certain degree of intelligence to the control system of air conditioning and lighting devices. Although the values provided by the sensors are already useful for decision-making, mathematical analysis allows studying the behavior of these variables in the room and defining the correct operating values and in the correct time periods. In addition, this information can be recorded for future review by users, as information about the state of the place in terms of temperature and lighting.

The use of mathematical methods of clustering and equation modeling are some of the many techniques that can be used to treat the data obtained from the sensors. Procedures such as data mining would allow an in-depth information analysis, which combined with more advanced hardware accuracy would make the percentage of savings and the operating thresholds of the devices more accurate and efficient.

VII. RECOMMENDATIONS

Based on the conclusions obtained from this work, several recommendations are made that, in the long term, could improve energy efficiency in a building. The proposed lighting improvements could be implemented when a room works with luminaires that operate independently of each other. Currently, these types of systems are not regularly found in buildings in Ecuador, so migration to autonomous lighting systems is recommended.

In this project we work with obtaining information about lighting and room temperature, for a subsequent mathematical analysis of the data. To improve the accuracy of the data obtained, it is recommended to carry out the mathematical processing at the same time as the data collection, a process that the Raspberry Pi used can carry out without any problem.

The data obtained by the sensors in this project does not reach 100% accuracy due to the hardware used, low cost devices and for experimental purposes. In order to achieve high performance in the system, it is recommended to use industrial-type devices, such as the Panasonic PIR sensor EKMB1101112, a sensor used in [9] that provides results with high accuracy.

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